CHAPTER 10.—ENGINE MAINTENANCE AND OPERATION

CHAPTER 1

THEORY AND CONSTRUCTION OF AIRCRAFT ENGINES

GENERAL

For an aircraft to remain in level unaccelerated flight, a thrust must be provided that is equal to and opposite in direction to the aircraft drag. This thrust, or propulsive force, is provided by a suitable type of heat engine.

All heat engines have in common the ability to convert heat energy into mechanical energy, by the flow of some fluid mass through the engine. In all cases, the heat energy is released at a point in the cycle where the pressure is high, relative to atmospheric.

These engines are customarily divided into groups or types depending upon:

(1) The working fluid used in the engine cycle,
(2) the means by which the mechanical energy is transmitted into a propulsive force, and
(3) the method of compressing the engine working fluid.

The types of engines are illustrated in figure 1–1.

Engine Type	*Major Means of Compression*	*Engine Working Fluid*	*Propulsive Working Fluid*
Turbojet.	Turbine-driven compressor.	Fuel/air mixture.	Same as engine working fluid.
Turboprop.	Turbine-driven compressor.	Fuel/air mixture.	Ambient air.
Ramjet.	Ram compression due to high flight speed.	Fuel/air mixture.	Same as engine working fluid.
Pulse-jet.	Compression due to combustion.	Fuel/air mixture.	Same as engine working fluid.
Reciprocating.	Reciprocating action of pistons.	Fuel/air mixture.	Ambient air.
Rocket.	Compression due to combustion.	Oxidizer/fuel mixture.	Same as engine working fluid.

FIGURE 1–1. Types of engines.

The propulsive force is obtained by the displacement of a working fluid (not necessarily the same fluid used within the engine) in a direction opposite to that in which the airplane is propelled. This is an application of Newton's third law of motion. Air is the principal fluid used for propulsion in every type of powerplant except the rocket, in which only the byproducts of combustion are accelerated and displaced.

The propellers of aircraft powered by reciprocating or turboprop engines accelerate a large mass of air through a small velocity change. The fluid (air) used for the propulsive force is a different quantity than that used within the engine to produce the mechanical energy. Turbojets, ramjets, and pulse-jets accelerate a smaller quantity of air through a large velocity change. They use the same working fluid for propulsive force that is used within the engine. A rocket carries its own oxidizer rather than using ambient air for combustion. It discharges the gaseous byproducts of combustion through the exhaust nozzle at an extremely high velocity.

Engines are further characterized by the means of compressing the working fluid before the addition of heat. The basic methods of compression are:

(1) The turbine-driven compressor (turbine engine).
(2) The positive displacement, piston-type com-

pressor (reciprocating engine).

(3) Ram compression due to forward flight speed (ramjet).

(4) Pressure rise due to combustion (pulse-jet and rocket).

A more specific description of the major engine types used in commercial aviation is given later in this chapter.

COMPARISON OF AIRCRAFT POWERPLANTS

In addition to the differences in the methods employed by the various types of powerplants for producing thrust, there are differences in their suitability for different types of aircraft. The following discussion points out some of the important characteristics which determine their suitability.

General Requirements

All engines must meet certain general requirements of efficiency, economy, and reliability. Besides being economical in fuel consumption, an aircraft engine must be economical (the cost of original procurement and the cost of maintenance) and it must meet exacting requirements of efficiency and low weight per horsepower ratio. It must be capable of sustained high-power output with no sacrifice in reliability; it must also have the durability to operate for long periods of time between overhauls. It needs to be as compact as possible, yet have easy accessibility for maintenance. It is required to be as vibration free as possible and be able to cover a wide range of power output at various speeds and altitudes.

These requirements dictate the use of ignition systems that will deliver the firing impulse to the spark plugs or igniter plugs at the proper time in all kinds of weather and under other adverse conditions. Fuel-metering devices are needed that will deliver fuel in the correct proportion to the air ingested by the engine regardless of the attitude, altitude, or type of weather in which the engine is operated. The engine needs a type of oil system that delivers oil under the proper pressure to all of the operating parts of the engine when it is running. Also, it must have a system of damping units to damp out the vibrations of the engine when it is operating.

Power and Weight

The useful output of all aircraft powerplants is thrust, the force which propels the aircraft. Since the reciprocating engine is rated in b.hp. (brake horsepower) and the gas turbine engine is rated in pounds of thrust, no direct comparison can be made. However, since the reciprocating engine/propeller combination receives its thrust from the propeller, a comparison can be made by converting the horsepower developed by the reciprocating engine to thrust.

If desired, the thrust of a gas turbine engine can be converted into t.hp. (thrust horsepower). But it is necessary to consider the speed of the aircraft. This conversion can be accomplished by using the formula:

$$\text{t.hp.} = \frac{\text{thrust x aircraft speed (m.p.h.)}}{\text{375 mile-pounds per hour}}.$$

The value 375 mile-pounds per hour is derived from the basic horsepower formula as follows:

$$1 \text{ hp.} = 33{,}000 \text{ ft.-lb. per minute.}$$

$$33{,}000 \times 60 = 1{,}980{,}000 \text{ ft.-lb. per hour.}$$

$$\frac{1{,}980{,}000}{5{,}280} = 375 \text{ mile-pounds per hour.}$$

One horsepower equals 33,000 ft.-lb. per minute or 375 mile-pounds per hour. Under static conditions, thrust is figured as equivalent to approximately 2.6 pounds per hour.

If a gas turbine is producing 4,000 pounds of thrust and the aircraft in which the engine is installed is traveling at 500 m.p.h., the t.hp. will be:

$$\frac{4000 \times 500}{375} = 5{,}333.33 \text{ t.hp.}$$

It is necessary to calculate the horsepower for each speed of an aircraft, since the horsepower varies with speed. Therefore, it is not practical to try to rate or compare the output of a turbine engine on a horsepower basis.

The aircraft engine operates at a relatively high percentage of its maximum power output throughout its service life. The aircraft engine is at full power output whenever a takeoff is made. It may hold this power for a period of time up to the limits set by the manufacturer. The engine is seldom held at a maximum power for more than 2 minutes, and usually not that long. Within a few seconds after lift-off, the power is reduced to a power that is used for climbing and that can be maintained for longer periods of time. After the aircraft has climbed to cruising altitude, the power of the engine(s) is further reduced to a cruise power which can be maintained for the duration of the flight.

If the weight of an engine per brake horsepower (called the specific weight of the engine) is decreased, the useful load that an aircraft can carry and the performance of the aircraft obviously are increased. Every excess pound of weight carried by an aircraft engine reduces its performance. Tremendous gains in reducing the weight of the aircraft engine through improvement in design and metallurgy have resulted in reciprocating engines now producing approximately 1 hp. for each pound of weight.

Fuel Economy

The basic parameter for describing the fuel economy of aircraft engines is usually specific fuel consumption. Specific fuel consumption for turbojets and ramjets is the fuel flow (lbs./hr.) divided by thrust (lbs.), and for reciprocating engines the fuel flow (lbs./hr.) divided by brake horsepower. These are called "thrust specific fuel consumption" and "brake specific fuel consumption," respectively. Equivalent specific fuel consumption is used for the turboprop engine and is the fuel flow in pounds per hour divided by a turboprop's equivalent shaft horsepower. Comparisons can be made between the various engines on a specific fuel consumption basis.

At low speed, the reciprocating and turbopropeller engines have better economy than the turbojet engines. However, at high speed, because of losses in propeller efficiency, the reciprocating or turbopropeller engine's efficiency becomes less than that of the turbojet. Figure 1–2 shows a comparison of average thrust specific fuel consumption of three types of engines at rated power at sea level.

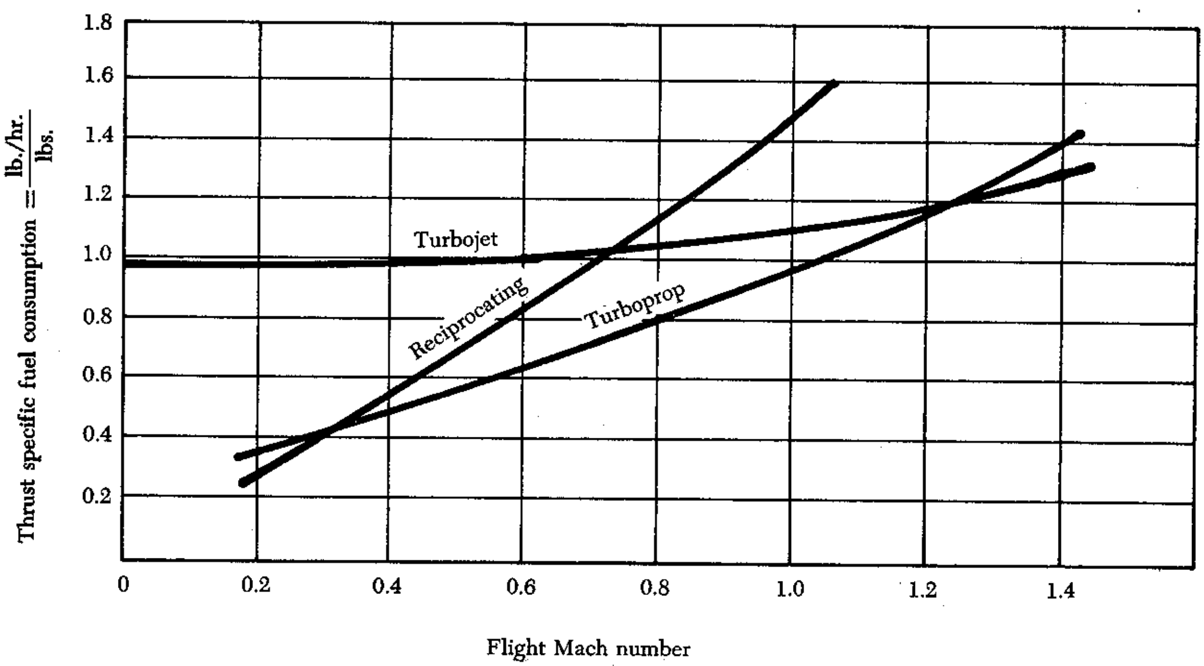


FIGURE 1–2. Comparison of fuel consumption for three types of engines at rated power at sea level.

Durability and Reliability

Durability and reliability are usually considered identical factors since it is difficult to mention one without including the other. An aircraft engine is reliable when it can perform at the specified ratings in widely varying flight attitudes and in extreme weather conditions. Standards of powerplant reliability are agreed upon by the FAA, the engine manufacturer, and the airframe manufacturer. The engine manufacturer ensures the reliability of his product by design, research, and testing. Close control of manufacturing and assembly procedures is maintained, and each engine is tested before it leaves the factory.

Durability is the amount of engine life obtained while maintaining the desired reliability. The fact that an engine has successfully completed its type or proof test indicates that it can be operated in a normal manner over a long period before requiring overhaul. However, no definite time interval between overhauls is specified or implied in the engine rating. The TBO (time between overhauls) varies with the operating conditions such as engine temperatures, amount of time the engine is operated at high-power settings, and the maintenance received.

Reliability and durability are thus built into the engine by the manufacturer, but the continued reliability of the engine is determined by the maintenance, overhaul, and operating personnel. Careful maintenance and overhaul methods, thorough periodical and preflight inspections, and strict observance of the operating limits established by the engine manufacturer will make engine failure a rare occurrence.

Operating Flexibility

Operating flexibility is the ability of an engine to run smoothly and give desired performance at all speeds from idling to full-power output. The aircraft engine must also function efficiently through all the variations in atmospheric conditions encountered in widespread operations.

Compactness

To effect proper streamlining and balancing of an aircraft, the shape and size of the engine must be as compact as possible. In single-engine aircraft, the shape and size of the engine also affect the view of the pilot, making a smaller engine better from this standpoint, in addition to reducing the drag created by a large frontal area.

Weight limitations, naturally, are closely related to the compactness requirement. The more elongated and spreadout an engine is, the more difficult it becomes to keep the specific weight within the allowable limits.

Powerplant Selection

Engine specific weight and specific fuel consumption were discussed in the previous paragraphs, but for certain design requirements, the final powerplant selection may be based on factors other than those which can be discussed from an analytical point of view. For that reason, a general discussion of powerplant selection is included here.

For aircraft whose cruising speeds will not exceed 250 m.p.h. the reciprocating engine is the usual choice. When economy is required in the low-speed range, the conventional reciprocating engine is chosen because of its excellent efficiency. When high-altitude performance is required, the turbosupercharged reciprocating engine may be chosen because it is capable of maintaining rated power to a high altitude (above 30,000 feet).

In the range of cruising speeds from 180 to 350 m.p.h. the turbopropeller engine performs better than other types of engines. It develops more power per pound of weight than does the reciprocating engine, thus allowing a greater fuel load or payload for engines of a given power. The maximum overall efficiency of a turboprop powerplant is less than that of a reciprocating engine at low speed. Turboprop engines operate most economically at high altitudes, but they have a slightly lower service ceiling than do turbosupercharged reciprocating engines. Economy of operation of turboprop engines, in terms of cargo-ton-miles per pound of fuel, will usually be poorer than that of reciprocating engines because cargo-type aircraft are usually designed for low-speed operation. On the other hand, cost of operation of the turboprop may approach that of the reciprocating engine because it burns cheaper fuel.

Aircraft intended to cruise from high subsonic speeds up to Mach 2.0 are powered by turbojet engines. Like the turboprop, the turbojet operates most efficiently at high altitudes. High-speed, turbojet-propelled aircraft fuel economy, in terms of miles per pound of fuel, is poorer than that attained at low speeds with reciprocating engines.

However, reciprocating engines are more complex in operation than other engines. Correct operation of reciprocating engines requires about twice the instrumentation required by turbojets or turboprops, and it requires several more controls. A change in power setting on some reciprocating engine installations may require the adjustment of five controls, but a change in power on a turbojet requires only a change in throttle setting. Furthermore, there are a greater number of critical temperatures and pressures to be watched on reciprocating engine installations than on turbojet or turboprop installations.

TYPES OF RECIPROCATING ENGINES

Many types of reciprocating engines have been designed. However, manufacturers have developed some designs that are used more commonly than others and are therefore recognized as conventional. Reciprocating engines may be classified according to cylinder arrangement with respect to the crankshaft (in-line, V-type, radial, and opposed) or according to the method of cooling (liquid cooled or air cooled). Actually, all engines are cooled by transferring excess heat to the surrounding air. In air-cooled engines, this heat transfer is direct from the cylinders to the air. In liquid-cooled engines, the heat is transferred from the cylinders to the coolant, which is then sent through tubing and cooled within a radiator placed in the airstream. The radiator must be large enough to cool the liquid efficiently. Heat is transferred to air more slowly than it is to a liquid. Therefore, it is necessary to provide thin metal fins on the cylinders of an air-cooled engine in order to have increased surface for sufficient heat transfer. Most aircraft engines are air cooled.

In-line Engines

An in-line engine generally has an even number of cylinders, although some three-cylinder engines have been constructed. This engine may be either liquid cooled or air cooled and has only one crankshaft, which is located either above or below the cylinders. If the engine is designed to operate with the cylinders below the crankshaft, it is called an inverted engine.

The in-line engine has a small frontal area and is better adapted to streamlining. When mounted with the cylinders in an inverted position, it offers the added advantages of a shorter landing gear and greater pilot visibility. The in-line engine has a higher weight-to-horsepower ratio than most other engines. With increase in engine size, the air cooled, in-line type offers additional handicaps to proper cooling; therefore, this type of engine is, to a large degree, confined to low- and medium-horsepower engines used in light aircraft.

Opposed or O-type Engines

The opposed-type engine, shown in figure 1–3, has two banks of cylinders directly opposite each other with a crankshaft in the center. The pistons of both cylinder banks are connected to the single crankshaft. Although the engine can be either liquid cooled or air cooled, the air-cooled version is used predominantly in aviation. It can be mounted with the cylinders in either a vertical or horizontal position.

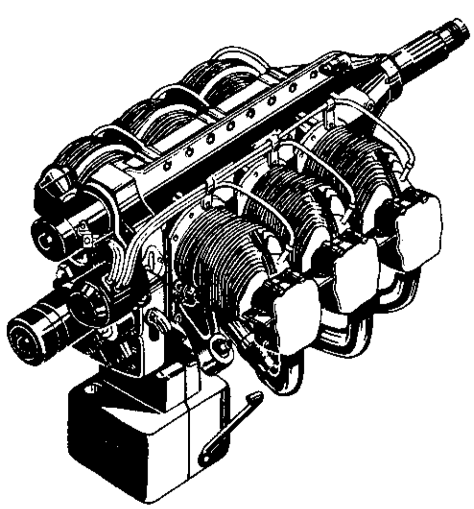


FIGURE 1–3. Opposed engine.

The opposed-type engine has a low weight-to-horsepower ratio, and its narrow silhouette makes it ideal for horizontal installation on the aircraft wings. Another advantage is its comparative freedom from vibration.

V-type Engines

In the V-type engines, the cylinders are arranged in two in-line banks generally set 60° apart. Most of the engines have 12 cylinders, which are either liquid cooled or air cooled. The engines are designated by a V, followed by a dash and the piston displacement in cubic inches, for example, V-1710.

Radial Engines

The radial engine consists of a row, or rows, of cylinders arranged radially about a central crankcase (see figure 1–4). This type of engine has proven to be very rugged and dependable. The number of cylinders composing a row may be either three, five, seven, or nine. Some radial engines have two rows of seven or nine cylinders arranged radially about the crankcase. One type has four rows of cylinders with seven cylinders in each row.

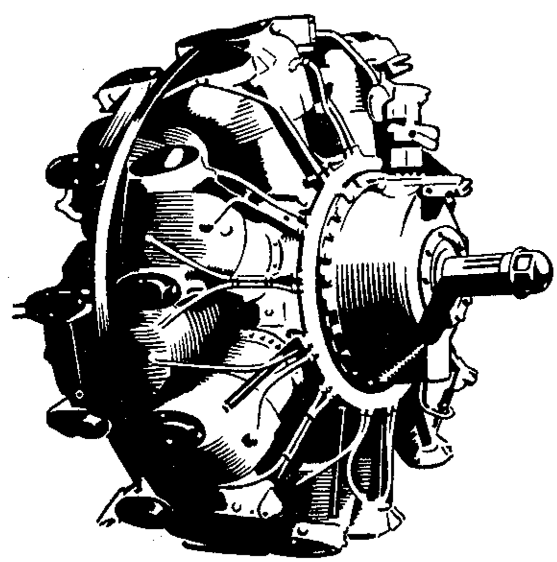


FIGURE 1–4. Radial engine.

The power output from the different sizes of radial engines varies from 100 to 3,800 horsepower.

RECIPROCATING ENGINE DESIGN AND CONSTRUCTION

The basic parts of a reciprocating engine are the crankcase, cylinders, pistons, connecting rods, valves, valve-operating mechanism, and crankshaft. In the head of each cylinder are the valves and spark plugs. One of the valves is in a passage leading from the induction system; the other is in a passage leading to the exhaust system. Inside each cylinder is a movable piston connected to a crankshaft by a connecting rod. Figure 1–5 illustrates the basic parts of a reciprocating engine.

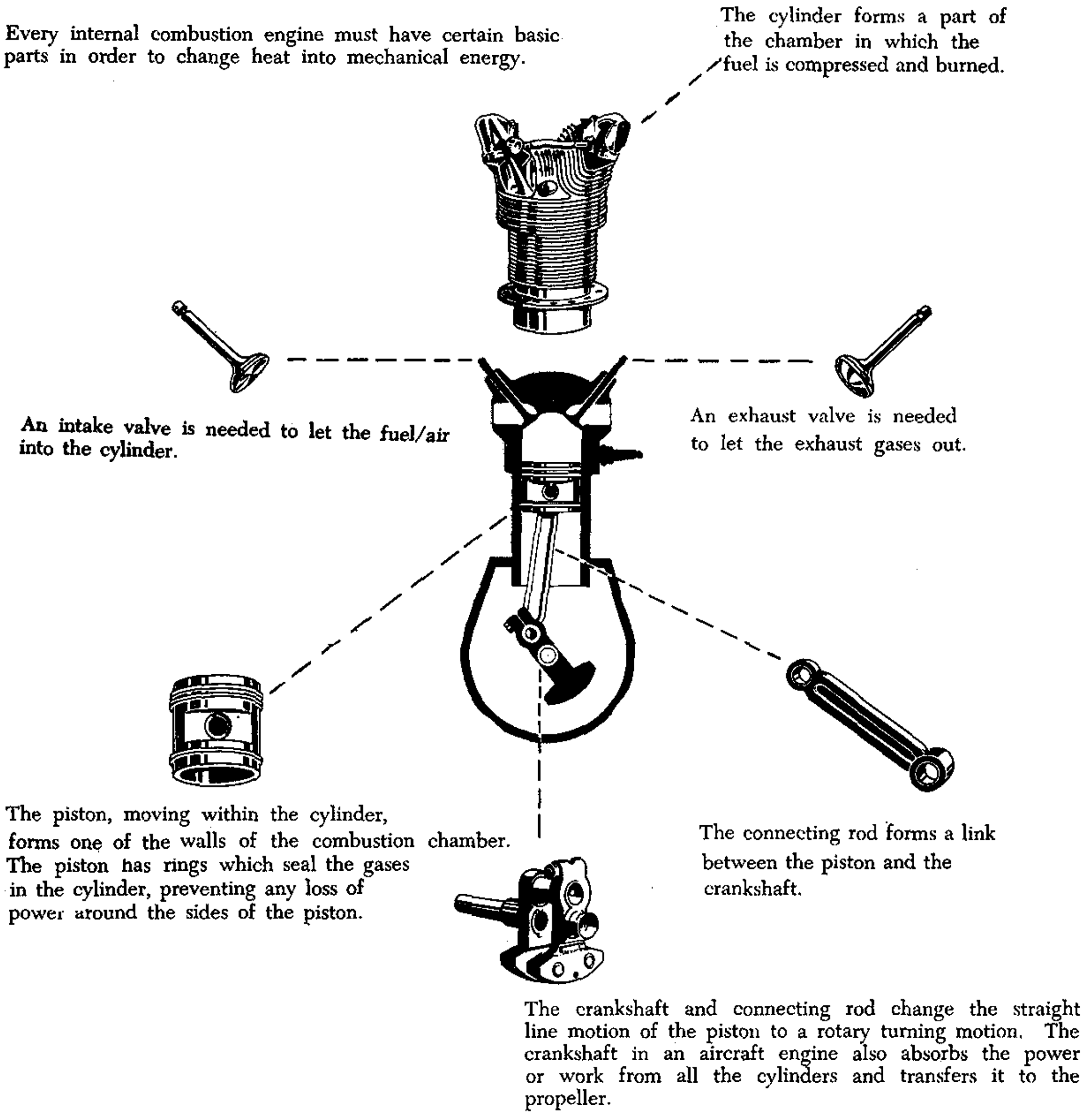


FIGURE 1–5. Basic parts of a reciprocating engine.

Crankcase Sections

The foundation of an engine is the crankcase. It contains the bearings in which the crankshaft revolves. Besides supporting itself, the crankcase must provide a tight enclosure for the lubricating oil and must support various external and internal mechanisms of the engine. It also provides support for attachment of the cylinder assemblies, and the powerplant to the aircraft. It must be sufficiently rigid and strong to prevent misalignment of the crankshaft and its bearings. Cast or forged aluminum alloy is generally used for crankcase construction because it is light and strong. Forged steel crankcases are used on some of the high-power output engines.

The crankcase is subjected to many variations of vibrational and other forces. Since the cylinders are fastened to the crankcase, the tremendous expansion forces tend to pull the cylinder off the crankcase. The unbalanced centrifugal and inertia forces of the crankshaft acting through the main bearing subject the crankcase to bending moments which change continuously in direction and magnitude. The crankcase must have sufficient stiffness to withstand these bending moments without objectional deflections. If the engine is equipped with a propeller reduction gear, the front or drive end will be subjected to additional forces.

In addition to the thrust forces developed by the propeller under high-power output, there are severe centrifugal and gyroscopic forces applied to the crankcase due to sudden changes in the direction of flight, such as those occurring during maneuvers of the airplane. Gyroscopic forces are, of course, particularly severe when a heavy propeller is installed.

Radial Engines

The engine shown in figure 1–6 is a single-row, nine-cylinder radial engine of relatively simple construction, having a one-piece nose and a two-section main crankcase.

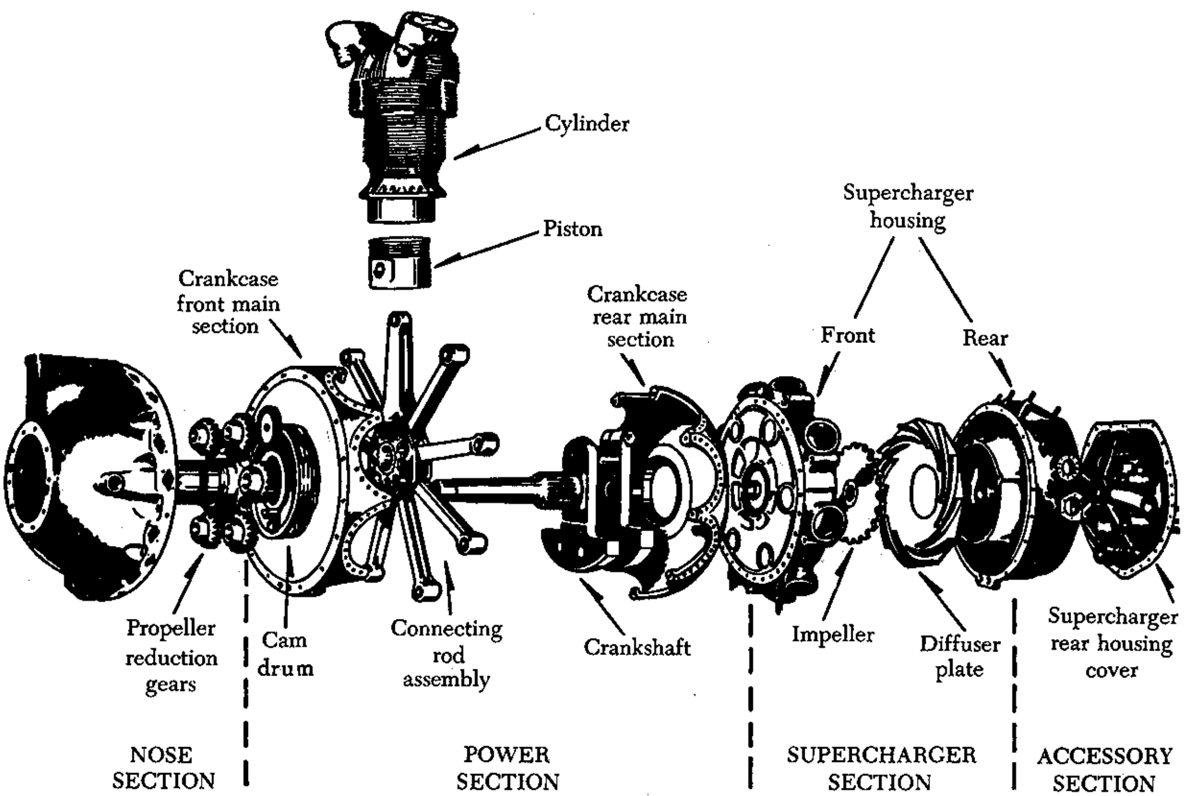


FIGURE 1–6. Engine sections.

The larger twin-row engines are of slightly more complex construction than the single-row engines. For example, the crankcase of the Wright R-3350 engine is composed of the crankcase front section, four crankcase main sections (the front main, the front center, the rear center, and the rear main sections), the rear cam and tappet housing, the supercharger front housing, the supercharger rear housing, and the supercharger rear housing cover. Pratt and Whitney engines of comparable size incorporate the same basic sections, although the construction and the nomenclature differ considerably.

Nose Section

The shape of nose sections varies considerably. In general, it is either tapered or round in order to place the metal under tension or compression instead of shear stresses. A tapered nose section is used quite frequently on direct-drive, low-powered engines, because extra space is not required to house the propeller reduction gear. It is usually cast of either aluminum alloy or magnesium since the low power developed and the use of a lightweight propeller do not require a more expensive forged nose section.

The nose section on engines which develop from 1,000 to 2,500 hp. is usually rounded and sometimes ribbed to get as much strength as possible. Aluminum alloy is the most widely used material because of its adaptability to forging processes and its vibration-absorbing characteristics.

The design and construction of the nose section is an important factor since it is subjected to a wide variation of forces and vibration. For instance, if the valve mechanism is located in front of the cylinders, the vibration and forces occurring at the tappet and guide assembly are applied near the flanged portion of the case. The forces created by the propeller reduction gear are applied to the case as a whole. Careful vibration surveys are conducted during the experimental testing of newly designed engines to see that these conditions will not become detrimental throughout the operating range of the engine.

The mounting of the propeller governor varies. On some engines it is located on the rear section, although this complicates the installation, especially if the propeller is operated or controlled by oil pressure, because of the distance between the governor and propeller. Where hydraulically operated propellers are used, it is good practice to mount the governor on the nose section as close to the propeller as possible to reduce the length of the oil passages. The governor is then driven either from gear teeth on the periphery of the bell gear or by some other suitable means.

Since the nose section transmits many varied forces to the main or power section, it must be properly secured to transmit the loads efficiently. It also must have intimate contact to give rapid and uniform heat conduction, and be oiltight to prevent leakage. This is usually accomplished by an offset or ground joint, secured by studs or capscrews.

On some of the larger engines, a small chamber is located on the bottom of the nose section to collect the oil. This is called the nose section oil sump.

Power Section

On engines equipped with a two-piece master rod and a solid-type crankshaft, the main or power crankcase section may be solid, usually of aluminum alloy. The front end of this section is open when the diaphragm plate in which the front main bearing is mounted is removed. The knuckle pins may be removed through this opening by a suitable knuckle-pin puller. The master rod is then removed by disassembling the split end and pulling the shank out through the master rod cylinder hole. There is also an engine equipped with this crankshaft and master rod arrangement which uses a split case crankcase held together by through bolts.

The split main section (aluminum or magnesium alloy) may be slightly more expensive, but permits better control over the quality of the casting or forging. The split main section is generally necessary when a solid master rod and a split-type crankshaft are used.

This portion of the engine is often called the power section, because it is here that the reciprocating motion of the piston is converted to rotary motion of the crankshaft.

Because of the tremendous loads and forces from the crankshaft assembly and the tendency of the cylinders to pull the crankcase apart, especially in extreme conditions when a high-powered engine is detonated, the main crankcase section must be very well designed and constructed. It is good practice to forge this section from aluminum alloy to obtain uniformity in the density of the metal and maximum strength. One large engine uses a forged alloy steel main section, which is slightly heavier but has very great strength. The design of the forged sections is usually such that both halves can be made in the same die in order to reduce manufacturing costs. Any variations can be taken care of during the machining operation. The two halves are joined on the center line of the cylinders and held together by suitable high-strength bolts.

The machined surfaces on which the cylinders are mounted are called cylinder pads. They are provided with a suitable means of retaining or fastening the cylinders to the crankcase. The general practice in securing the cylinder flange to the pad is to mount studs in threaded holes in the crankcase.

On engines equipped with the steel main section, capscrews are being utilized because the threads may be tapped in the stronger material and are not as likely to be stripped or stretched by installing and removing threaded members.

The inner portion of the cylinder pads are sometimes chamfered or tapered to permit the installation of a large rubber O-ring around the cylinder skirt, which effectively seals the joint between the cylinder and the crankcase pads against oil leakage.

Because oil is thrown about the crankcase, especially on inverted in-line and radial-type engines, the cylinder skirts extend a considerable distance into the crankcase sections to reduce the flow of oil into the inverted cylinders. The piston and ring assemblies, of course, have to be arranged so that they will throw out the oil splashed directly into them.

As mentioned previously, the nose section is secured to one side of the main section unit, and the diffuser or blower section is attached to the other side.

Diffuser Section

The diffuser or supercharger section generally is cast of aluminum alloy, although, in a few cases, the lighter magnesium alloy is used.

Mounting lugs are spaced about the periphery of this section to attach the engine assembly to the engine mount or framework provided for attaching the powerplant to the fuselage of single-engine aircraft or to the wing nacelle structure of multiengine aircraft. The mounting lugs may be either integral with the diffuser section or detachable, as in the case of flexible or dynamic engine mounts.

The mounting arrangement supports the entire powerplant including the propeller, and therefore is designed to provide ample strength for rapid maneuvers or other loadings.

Because of the elongation and contraction of the cylinders, the intake pipes which carry the mixture from the diffuser chamber through the intake valve ports are arranged to provide a slip joint which must be leakproof. The atmospheric pressure on the outside of the case of an unsupercharged engine will be higher than on the inside, especially when the engine is operating at idling speed. If the engine is equipped with a supercharger and operated at full throttle, the pressure will be considerably higher on the inside than on the outside of the case.

If the slip joint connection has a slight leakage, the engine may idle fast due to a slight leaning of the mixture. If the leak is quite large, it may not idle at all. At open throttle, a small leak probably would not be noticeable in operation of the engine, but the slight leaning of the fuel/air mixture might cause detonation or damage to the valves and valve seats.

On some radial engines, the intake pipe has considerable length and on some in-line engines, the intake pipe is at right angles to the cylinders. In these cases, flexibility of the intake pipe or its arrangement eliminates the need for a slip joint. In any case, the engine induction system must be arranged so that it will not leak air and change the desired fuel/air ratio.

Accessory Section

The accessory (rear) section usually is of cast construction, and the material may be either aluminum alloy, which is used most widely, or magnesium, which has been used to some extent. On some engines, it is cast in one piece and provided with means for mounting the accessories, such as magnetos, carburetors, and fuel, oil, and vacuum pumps, and starter, generator, etc., in the various locations required to facilitate accessibility. Other adaptations consist of an aluminum alloy casting and a separate cast magnesium cover plate on which the accessory mounts are arranged.

Recent design practice has been toward standardizing the mounting arrangement for the various accessories so that they will be interchangeable on different makes of engines. For example, the increased demands for electric current on large aircraft and the requirements of higher starting torque on powerful engines have resulted in an increase in the size of starters and generators. This means that a greater number of mounting bolts must be provided and, in some cases, the entire rear section strengthened.

Accessory drive shafts are mounted in suitable bronze bushings located in the diffuser and rear sections. These shafts extend into the rear section and are fitted with suitable gears from which power takeoffs or drive arrangements are carried out to the accessory mounting pads. In this manner the various gear ratios can be arranged to give the proper drive speed to magneto, pump, and other accessories to obtain correct timing or functioning.

In some cases there is a duplication of drives, such as the tachometer drive, to connect instruments located at separate stations.

The accessory section provides a mounting place for the carburetor, or master control, fuel injection pumps, engine-driven fuel pump, tachometer generator, synchronizing generator for the engine analyzer, oil filter, and oil pressure relief valve.

Accessory Gear Trains

Gear trains, containing both spur- and bevel-type gears, are used in the different types of engines for driving engine components and accessories. Spur-type gears are generally used to drive the heavier loaded accessories or those requiring the least play or backlash in the gear train. Bevel gears permit angular location of short stub shafts leading to the various accessory mounting pads.

Practically all high-powered engines are equipped with a supercharger. From 75 to 125 hp. may be required to drive the supercharger. The acceleration and deceleration forces imposed on the supercharger gear train when opening and closing the throttle make some kind of antishock device necessary to relieve excessive loads. The current practice on large radial engines is to use a main accessory drive gear which is fitted with several springs between the rim of the gear and drive shaft. This device, called the spring-loaded accessory drive gear, permits absorption of forces of high magnitude, preventing damage to the accessory gear trains. When an engine is equipped with a two-speed supercharger, the oil-pressure operated clutches act as shock absorbers to protect the supercharger gear train.

On the low-powered, opposed, and in-line engines, the accessory gear trains are usually simple arrangements. Many of these engines use synthetic rubber or spring couplings to protect the magneto and generator gear trains from excessive loads.

Opposed and In-line Types

The crankcases used on engines having opposed or in-line cylinder arrangements vary in form for the different types of engines, but in general they are approximately cylindrical. One or more sides are surfaced to serve as a base to which the cylinders are attached by means of capscrews, bolts, or studs. These accurately machined surfaces are frequently referred to as cylinder pads.

The crankshaft is carried in a position parallel to the longitudinal axis of the crankcase and is generally supported by a main bearing between each throw. The crankshaft main bearings must be supported rigidly in the crankcase. This usually is accomplished by means of transverse webs in the crankcase, one for each main bearing. The webs form an integral part of the structure and, in addition to supporting the main bearings, add to the strength of the entire case.

The crankcase is divided into two sections in a

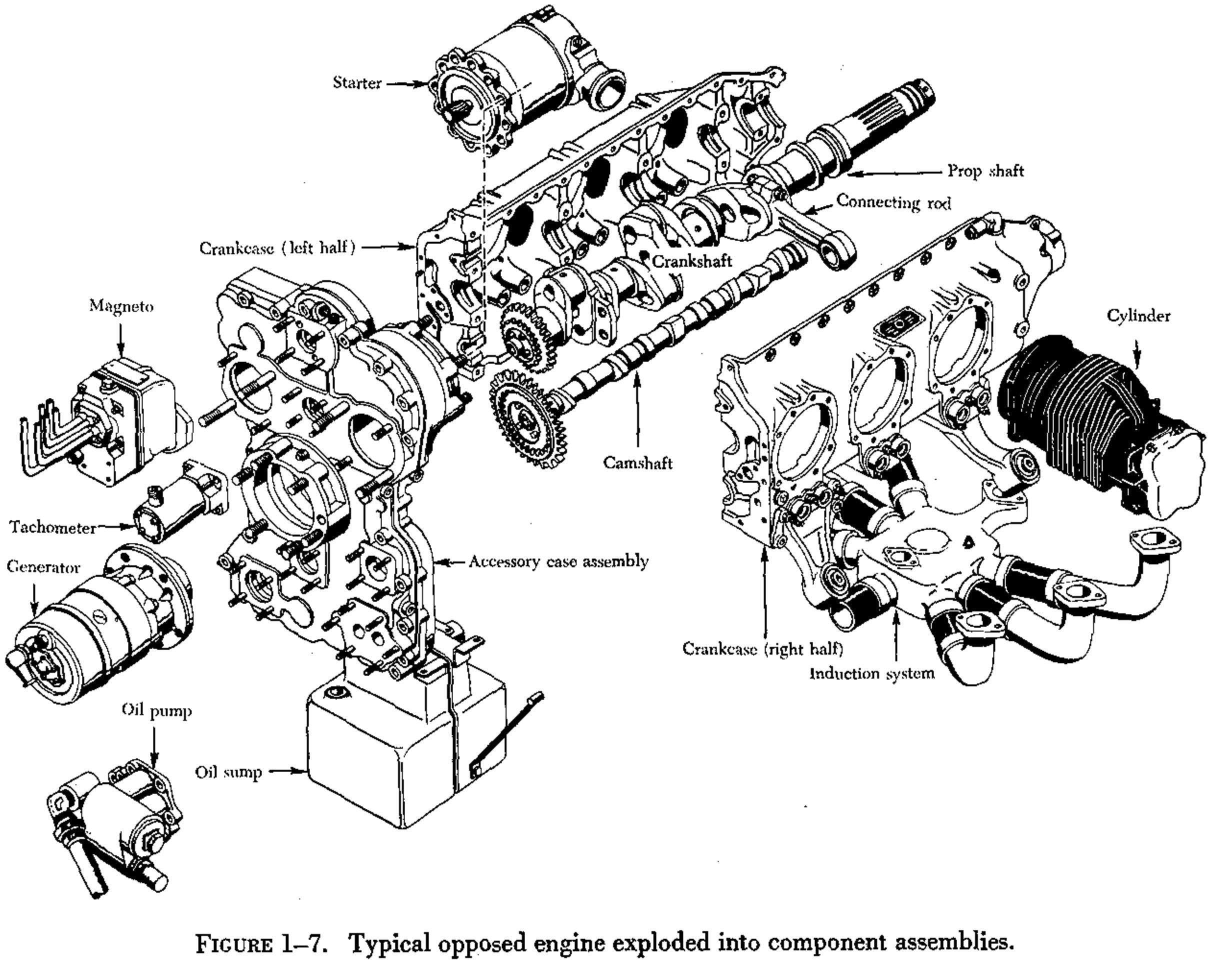


FIGURE 1–7. Typical opposed engine exploded into component assemblies.

longitudinal plane. This division may be in the plane of the crankshaft so that one-half of the main bearing (and sometimes camshaft bearings) are carried in one section of the case and the other half in the opposite section. (See figure 1–7.) Another method is to divide the case in such a manner that the main bearings are secured to only one section of the case on which the cylinders are attached, thereby providing means of removing a section of the crankcase for inspection without disturbing the bearing adjustment.

CRANKSHAFTS

The crankshaft is the backbone of the reciprocating engine. It is subjected to most of the forces developed by the engine. Its main purpose is to transform the reciprocating motion of the piston and connecting rod into rotary motion for rotation of the propeller. The crankshaft, as the name implies, is a shaft composed of one or more cranks located at specified points along its length. The cranks, or throws, are formed by forging offsets into a shaft before it is machined. Since crankshafts must be very strong, they generally are forged from a very strong alloy, such as chromium-nickel-molybdenum steel.

A crankshaft may be of single-piece or multipiece construction. Figure 1–8 shows two representative types of solid crankshafts used in aircraft engines. The four-throw construction may be used either on four-cylinder horizontal opposed or four-cylinder in-line engines.

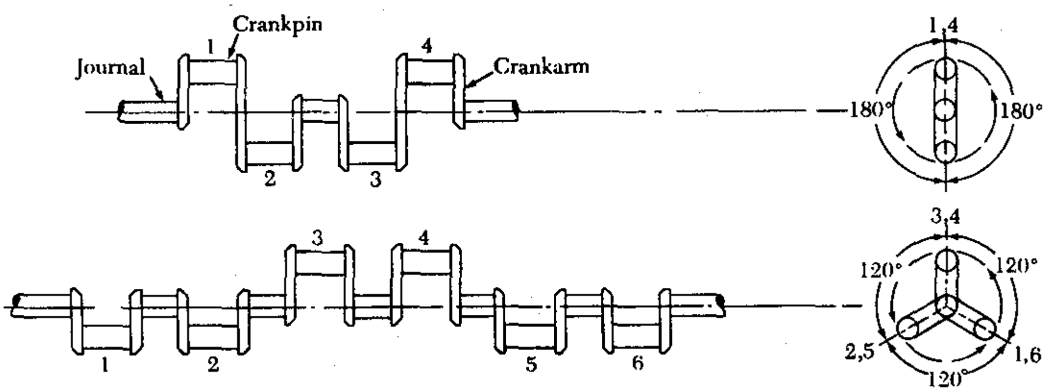


FIGURE 1–8. Solid types of crankshafts.

The six-throw shaft is used on six-cylinder in-line engines, 12-cylinder V-type engines, and six-cylinder opposed engines.

Crankshafts of radial engines may be the single-throw, two-throw, or four-throw type, depending on whether the engine is the single-row, twin-row, or four-row type. A single-throw radial engine crankshaft is shown in figure 1–9.

No matter how many throws it may have, each crankshaft has three main parts—a journal, crankpin, and crank cheek. Counterweights and dampers, although not a true part of a crankshaft, are usually attached to it to reduce engine vibration.

The journal is supported by, and rotates in, a main bearing. It serves as the center of rotation of the crankshaft. It is surface-hardened to reduce wear.

The crankpin is the section to which the connecting rod is attached. It is off-center from the main journals and is often called the throw. Two crank cheeks and a crankpin make a throw. When a force is applied to the crankpin in any direction other than parallel or perpendicular to and through the center line of the crankshaft, it will cause the crankshaft to rotate. The outer surface is hardened by nitriding to increase its resistance to wear and to provide the required bearing surface. The crankpin is usually hollow. This reduces the total weight of the crankshaft and provides a passage for the transfer of lubricating oil. The hollow crankpin also serves as a chamber for collecting sludge, carbon deposits, and other foreign material. Centrifugal force throws these substances to the outside of the chamber and thus keeps them from reaching the connecting-rod bearing surface. On some engines a passage is drilled in the crank cheek to allow oil

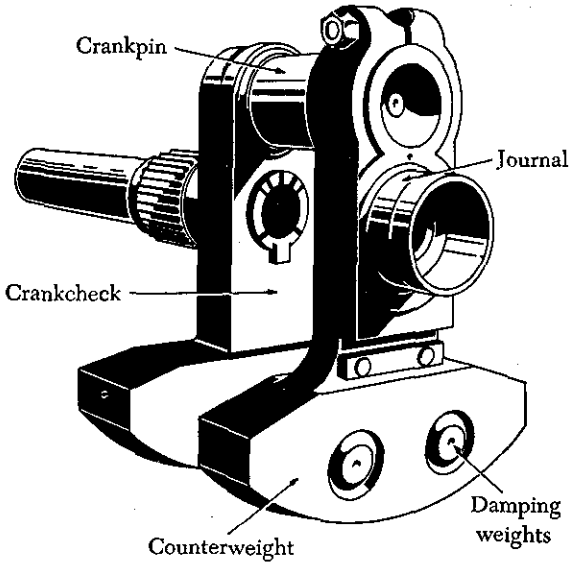


FIGURE 1–9. A single-throw radial engine crankshaft.

from the hollow crankshaft to be sprayed on the cylinder walls.

The crank cheek connects the crankpin to the main journal. In some designs, the cheek extends beyond the journal and carries a counterweight to balance the crankshaft. The crank cheek must be of sturdy construction to obtain the required rigidity between the crankpin and the journal.

In all cases, the type of crankshaft and the number of crankpins must correspond with the cylinder arrangement of the engine. The position of the cranks on the crankshaft in relation to the other cranks of the same shaft is expressed in degrees.

The simplest crankshaft is the single-throw or 360° type. This type is used in a single-row radial engine. It can be constructed in one or two pieces. Two main bearings (one on each end) are provided when this type of crankshaft is used.

The double-throw or 180° crankshaft is used on double-row radial engines. In the radial-type engine, one throw is provided for each row of cylinders.

Crankshaft Balance

Excessive vibration in an engine not only results in fatigue failure of the metal structures, but also causes the moving parts to wear rapidly. In some instances, excessive vibration is caused by a crankshaft which is not balanced. Crankshafts are balanced for static balance and dynamic balance.

A crankshaft is statically balanced when the weight of the entire assembly of crankpins, crank cheeks, and counterweights is balanced around the axis of rotation. When testing the crankshaft for static balance, it is placed on two knife edges. If the shaft tends to turn toward any one position during the test, it is out of static balance.

A crankshaft is dynamically balanced when all the forces created by crankshaft rotation and power impulses are balanced within themselves so that little or no vibration is produced when the engine is operating. To reduce vibration to a minimum during engine operation, dynamic dampers are incorporated on the crankshaft. A dynamic damper is merely a pendulum which is so fastened to the crankshaft that it is free to move in a small arc. It is incorporated in the counterweight assembly. Some crankshafts incorporate two or more of these assemblies, each being attached to a different crank cheek. The distance the pendulum moves and its vibrating frequency correspond to the frequency of the power impulses of the engine. When the vibration frequency of the crankshaft occurs, the pendulum oscillates out of time with the crankshaft vibration, thus reducing vibration to a minimum.

Dynamic Dampers

The construction of the dynamic damper used in one engine consists of a movable slotted-steel counterweight attached to the crank cheek. Two spool-shaped steel pins extend into the slot and pass through oversized holes in the counterweight and crank cheek. The difference in the diameter between the pins and the holes provides a pendulum effect. An analogy of the functioning of a dynamic damper is shown in figure 1–10.

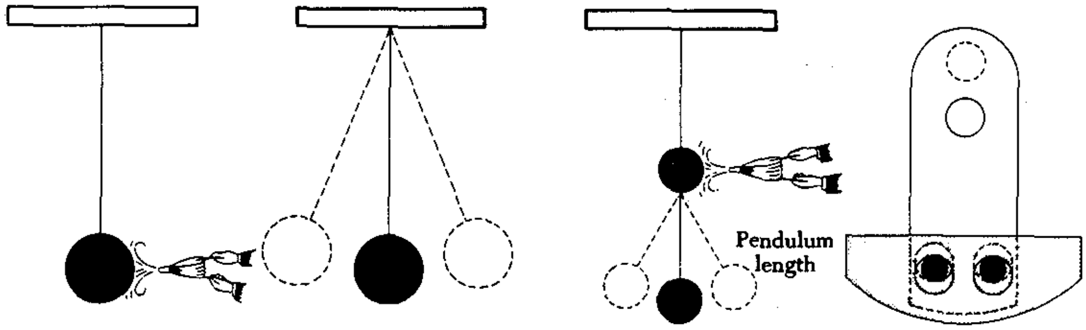
CONNECTING RODS

The connecting rod is the link which transmits forces between the piston and the crankshaft. Connecting rods must be strong enough to remain rigid under load and yet be light enough to reduce the inertia forces which are produced when the rod and piston stop, change direction, and start again at the end of each stroke.

There are three types of connecting-rod assemblies: (1) The plain-type connecting rod, (2) the fork-and-blade connecting rod, and (3) the master-and-articulated-rod assembly. (See figure 1–11.)

Master-and-Articulated Rod Assembly

The master-and-articulated rod assembly is commonly used in radial engines. In a radial engine the piston in one cylinder in each row is connected to the crankshaft by a master rod. All other pistons in the row are connected to the master rod by an



If a simple pendulum is given a series of regular impulses at a speed corresponding to its natural frequency (using a bellows to simulate a power impulse in an engine) it will commence swinging, or vibrating, back and forth from the impulses. Another pendulum, suspended from the first, would absorb the impulses and swing itself, leaving the first stationary. The dynamic damper is a short pendulum hung on the crankshaft and tuned to the frequency of the power impulses to absorb vibration in the same manner.

FIGURE 1–10. Principles of a dynamic damper.

articulated rod. In an 18-cylinder engine which has two rows of cylinders, there are two master rods and 16 articulated rods. The articulated rods are constructed of forged steel alloy in either the I- or H-shape, denoting the cross-sectional shape. Bronze bushings are pressed into the bores in each end of the articulated rod to provide knuckle-pin and piston-pin bearings.

The master rod serves as the connecting link between the piston pin and the crankpin. The crankpin end, or the "big end," contains the crankpin or master rod bearing. Flanges around the big end provide for the attachment of the articulated rods. The articulated rods are attached to the master rod by knuckle pins, which are pressed into holes in the master rod flanges during assembly. A plain bearing, usually called a piston-pin bushing, is installed in the piston end of the master rod to receive the piston pin.

When a crankshaft of the split-spline or split-clamp type is employed, a one-piece master rod is used. The master and articulated rods are assembled and then installed on the crankpin; the crankshaft sections are then joined together. In engines that use the one-piece type of crankshaft, the big end of the master rod is split, as is the master rod bearing. The main part of the master rod is installed on the crankpin; then the bearing cap is set in place and bolted to the master rod.

The centers of the knuckle pins do not coincide with the center of the crankpin. Thus, while the crankpin center describes a true circle for each revolution of the crankshaft, the centers of the knuckle pins describe an elliptical path (see figure 1–12).

The elliptical paths are symmetrical about a center line through the master rod cylinder. It can be seen that the major diameters of the ellipses are not the same. Thus, the link rods will have varying degrees of angularity relative to the center of the crank throw.

Because of the varying angularity of the link rods and the elliptical motion of the knuckle pins, all pistons do not move an equal amount in each cylinder for a given number of degrees of crank throw movement. This variation in piston position between cylinders can have considerable effect on engine operation. To minimize the effect of these factors on valve and ignition timing, the knuckle-pin holes in the master rod flange are not equidistant from the center of the crankpin, thereby offsetting to an extent the effect of the link rod angularity.

Another method of minimizing the adverse effects on engine operation is to use a compensated magneto. In this magneto the breaker cam has a number of lobes equal to the number of cylinders on the engine. To compensate for the variation in piston position due to link rod angularity, the breaker cam lobes are ground with uneven spacing. This allows the breaker contacts to open when the piston is in the correct firing position. This will be further outlined during the discussion on ignition timing in Chapter 4.

Knuckle Pins

The knuckle pins are of solid construction except for the oil passages drilled in the pins, which lubri-

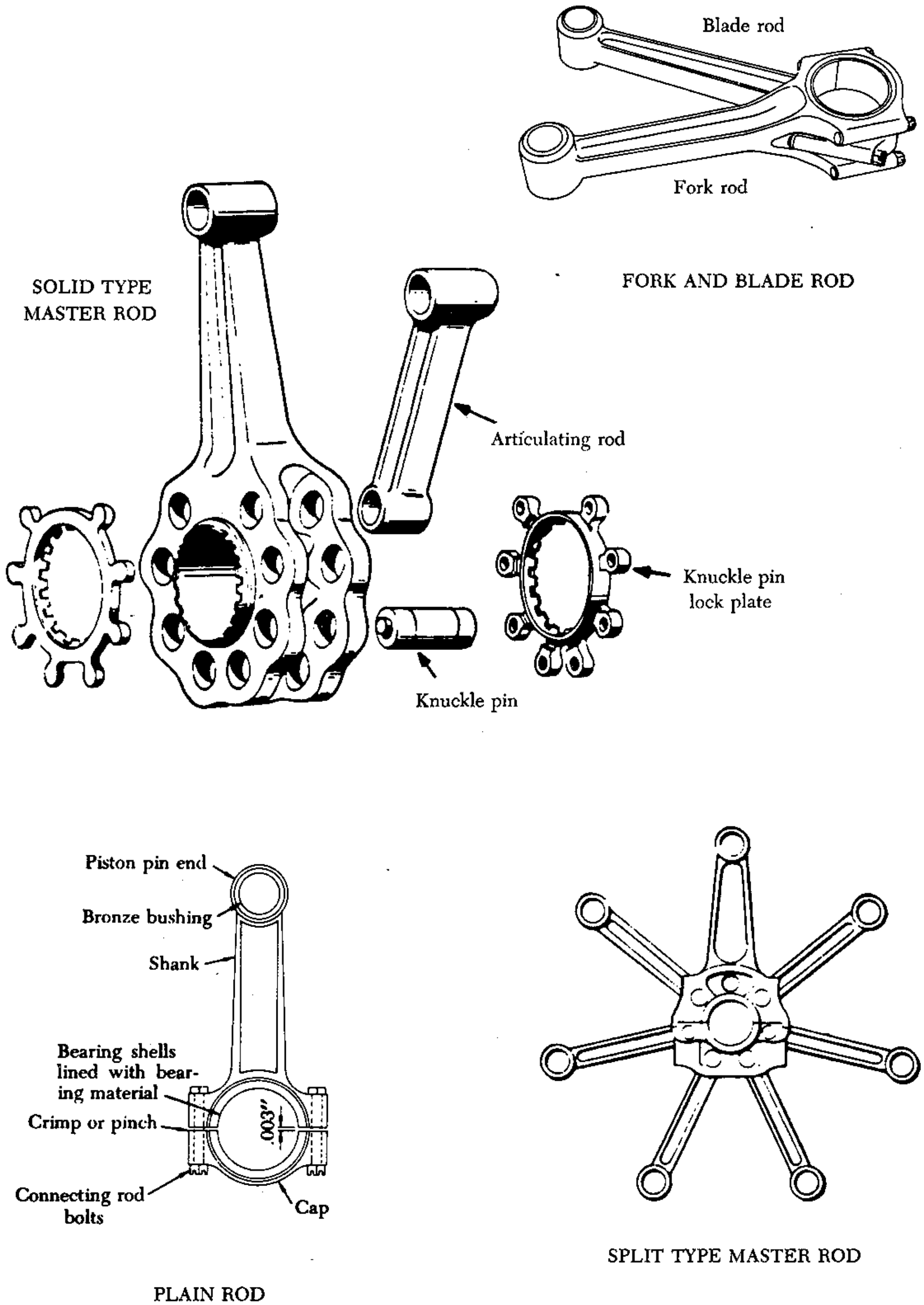


Figure 1–11. Connecting rod assemblies.

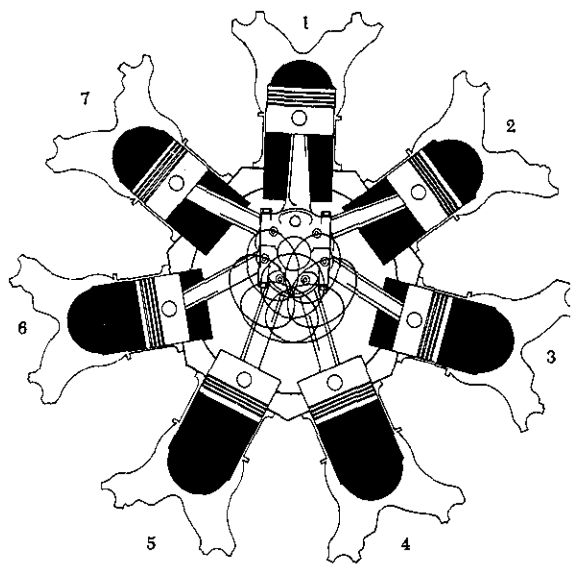


FIGURE 1–12. Elliptical travel path of knuckle pins in an articulated rod assembly.

cate the knuckle-pin bushings. These pins may be installed by pressing into holes in the master rod flanges so that they are prevented from turning in the master rod. Knuckle pins may also be installed with a loose fit so that they can turn in the master rod flange holes, and also turn in the articulating rod bushings. These are called "full-floating" knuckle pins. In either type of installation a lock plate on each side retains the knuckle pin and prevents a lateral movement of it.

Plain-Type Connecting Rods

Plain-type connecting rods are used in in-line and opposed engines. The end of the rod attached to the crankpin is fitted with a cap and a two-piece bearing. The bearing cap is held on the end of the rod by bolts or studs. To maintain proper fit and balance, connecting rods should always be replaced in the same cylinder and in the same relative position.

Fork-and-Blade Rod Assembly

The fork-and-blade rod assembly is used primarily in V-type engines. The forked rod is split at the crankpin end to allow space for the blade rod to fit between the prongs. A single two-piece bearing is used on the crankshaft end of the rod.

PISTONS

The piston of a reciprocating engine is a cylindrical member which moves back and forth within a steel cylinder. The piston acts as a moving wall within the combustion chamber. As the piston moves down in the cylinder, it draws in the fuel/air mixture. As it moves upward, it compresses the charge, ignition occurs, and the expanding gases force the piston downward. This force is transmitted to the crankshaft through the connecting rod. On the return upward stroke, the piston forces the exhaust gases from the cylinder.

Piston Construction

The majority of aircraft engine pistons are machined from aluminum alloy forgings. Grooves are machined in the outside surface of the piston to receive the piston rings, and cooling fins are provided on the inside of the piston for greater heat transfer to the engine oil.

Pistons may be either the trunk type or the slipper type; both are shown in figure 1–13. Slipper-type pistons are not used in modern, high-powered engines because they do not provide adequate strength or wear resistance. The top face of the piston, or head, may be either flat, convex, or concave. Recesses may be machined in the piston head to prevent interference with the valves.

As many as six grooves may be machined around the piston to accommodate the compression rings and oil rings. (See figure 1–13.) The compression rings are installed in the three uppermost grooves; the oil control rings are installed immediately above the piston pin. The piston is usually drilled at the oil control ring grooves to allow surplus oil scraped from the cylinder walls by the oil control rings to pass back into the crankcase. An oil scraper ring is installed at the base of the piston wall or skirt to prevent excessive oil consumption. The portions of the piston walls that lie between each pair of ring grooves are called the ring lands.

In addition to acting as a guide for the piston head, the piston skirt incorporates the piston-pin bosses. The piston-pin bosses are of heavy construction to enable the heavy load on the piston head to be transferred to the piston pin.

Piston Pin

The piston pin joins the piston to the connecting rod. It is machined in the form of a tube from a nickel steel alloy forging, casehardened and ground. The piston pin is sometimes called a wristpin because of the similarity between the relative motions of the piston and the articulated rod and that of the human arm.

The piston pin used in modern aircraft engines is the full-floating type, so called because the pin is

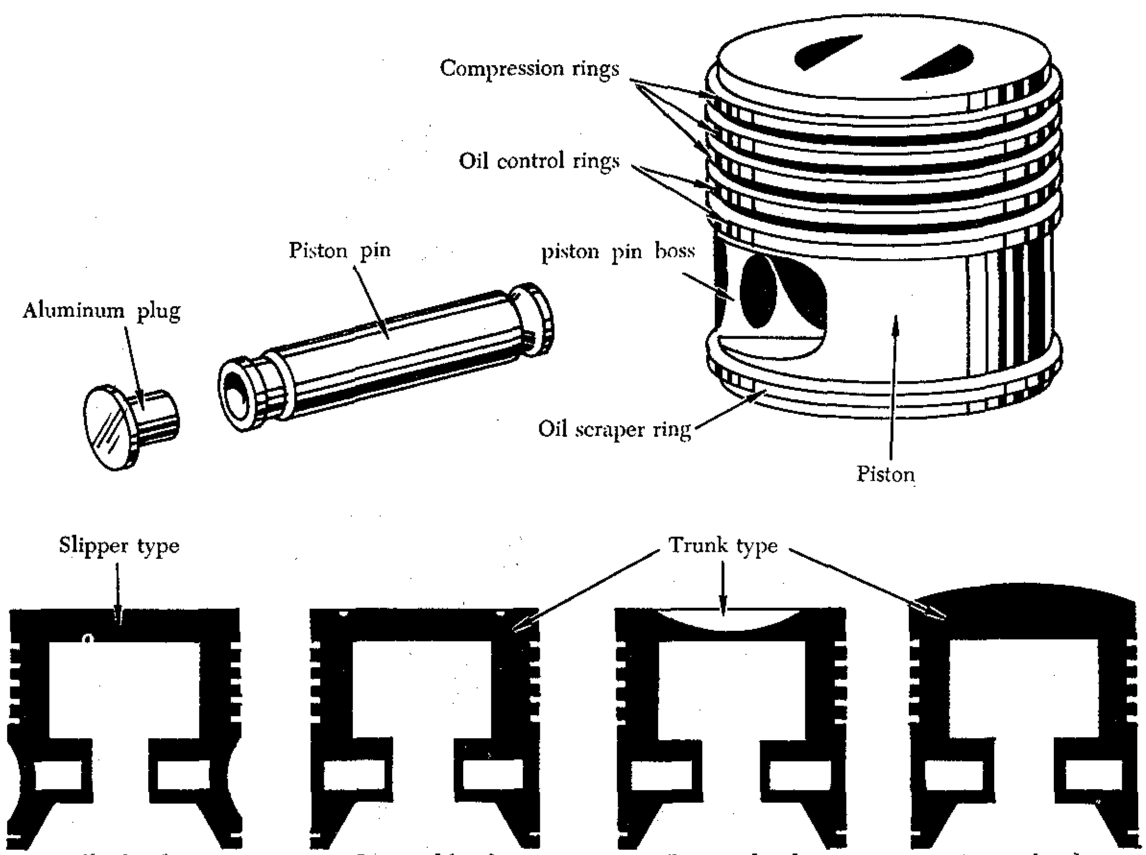


FIGURE 1–13. Piston assembly and types of pistons.

free to rotate in both the piston and in the connecting rod piston-pin bearing.

The piston pin must be held in place to prevent the pin ends from scoring the cylinder walls. In earlier engines, spring coils were installed in grooves in the piston-pin bores at either end of the pin. The current practice is to install a plug of relatively soft aluminum in the pin ends to provide a good bearing surface against the cylinder wall.

PISTON RINGS

The piston rings prevent leakage of gas pressure from the combustion chamber and reduce to a minimum the seepage of oil into the combustion chamber. The rings fit into the piston grooves but spring out to press against the cylinder walls; when properly lubricated, the rings form an effective gas seal.

Piston Ring Construction

Most piston rings are made of high-grade cast iron. After the rings are made, they are ground to the cross section desired. They are then split so that they can be slipped over the outside of the piston and into the ring grooves which are machined in the piston wall. Since their purpose is to seal the clearance between the piston and the cylinder wall, they must fit the cylinder wall snugly enough to provide a gastight fit; they must exert equal pressure at all points on the cylinder wall; and they must make a gastight fit against the sides of the ring grooves.

Gray cast iron is most often used in making piston rings. However, many other materials have been tried. In some engines, chrome-plated mild steel piston rings are used in the top compression ring groove because these rings can better withstand the high temperatures present at this point.

Compression Ring

The purpose of the compression rings is to prevent the escape of gas past the piston during engine operation. They are placed in the ring grooves immediately below the piston head. The number of compression rings used on each piston is determined by the type of engine and its design, although most aircraft engines use two compression rings plus one or more oil control rings.

The cross section of the ring is either rectangular or wedge shaped with a tapered face. The tapered face presents a narrow bearing edge to the cylinder wall which helps to reduce friction and provide better sealing.

Oil Control Rings

Oil control rings are placed in the grooves immediately below the compression rings and above the piston pin bores. There may be one or more oil control rings per piston; two rings may be installed in the same groove, or they may be installed in separate grooves. Oil control rings regulate the thickness of the oil film on the cylinder wall. If too much oil enters the combustion chamber, it will burn and leave a thick coating of carbon on the combustion chamber walls, the piston head, the spark plugs, and the valve heads. This carbon can cause the valves and piston rings to stick if it enters the ring grooves or valve guides. In addition, the carbon can cause spark plug misfiring as well as detonation, preignition, or excessive oil consumption. To allow the surplus oil to return to the crankcase, holes are drilled in the piston ring grooves or in the lands next to these grooves.

Oil Scraper Ring

The oil scraper ring usually has a beveled face and is installed in the groove at the bottom of the piston skirt. The ring is installed with the scraping edge away from the piston head or in the reverse position, depending upon cylinder position and the engine series. In the reverse position, the scraper ring retains the surplus oil above the ring on the upward piston stroke, and this oil is returned to the crankcase by the oil control rings on the downward stroke.

CYLINDERS

The portion of the engine in which the power is developed is called the cylinder. The cylinder provides a combustion chamber where the burning and expansion of gases take place, and it houses the piston and the connecting rod.

There are four major factors that need to be considered in the design and construction of the cylinder assembly. These are:

(1) It must be strong enough to withstand the internal pressures developed during engine operation.

(2) It must be constructed of a lightweight metal to keep down engine weight.

(3) It must have good heat-conducting properties for efficient cooling.

(4) It must be comparatively easy and inexpensive to manufacture, inspect, and maintain.

The head is either produced singly for each cylinder in air-cooled engines, or is cast "in-block" (all cylinder heads in one block) for liquid-cooled engines. The cylinder head of an air-cooled engine is generally made of aluminum alloy, because aluminum alloy is a good conductor of heat and its light weight reduces the overall engine weight. Cylinder heads are forged or die-cast for greater strength. The inner shape of a cylinder head may be flat, semispherical, or peaked, in the form of a house roof. The semispherical type has proved most satisfactory because it is stronger and aids in a more rapid and thorough scavenging of the exhaust gases.

The cylinder used in the air-cooled engine is the overhead valve type shown in figure 1–14. Each cylinder is an assembly of two major parts: (1) The cylinder head, and (2) the cylinder barrel. At assembly, the cylinder head is expanded by heating and then screwed down on the cylinder barrel which

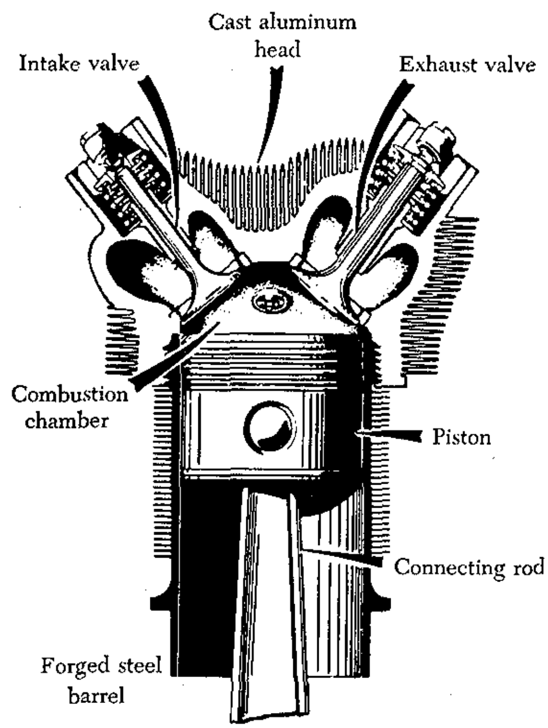


FIGURE 1–14. Cutaway view of the cylinder assembly.

has been chilled; thus, when the head cools and contracts, and the barrel warms up and expands, a gastight joint results. While the majority of the cylinders used are constructed in this manner, some are one-piece aluminum alloy sand castings. The piston bore of a sand cast cylinder is fitted with a steel liner which extends the full length of the cylinder barrel section and projects below the cylinder flange of the casting. This liner is easily removed, and a new one can be installed in the field.

Cylinder Heads

The purpose of the cylinder head is to provide a place for combustion of the fuel/air mixture and to give the cylinder more heat conductivity for adequate cooling. The fuel/air mixture is ignited by the spark in the combustion chamber and commences burning as the piston travels toward top dead center on the compression stroke. The ignited charge is rapidly expanding at this time, and pressure is increasing so that as the piston travels through the top dead center position, it is driven downward on the power stroke. The intake and exhaust valve ports are located in the cylinder head along with the spark plugs and the intake and exhaust valve actuating mechanisms.

After casting, the spark plug bushings, valve guides, rocker arm bushings, and valve seats are installed in the cylinder head. Spark plug openings may be fitted with bronze or steel bushings that are shrunk and screwed into the openings. Stainless steel Heli-Coil spark plug inserts are used in many engines currently manufactured. Bronze or steel valve guides are usually shrunk or screwed into drilled openings in the cylinder head to provide guides for the valve stems. These are generally located at an angle to the center line of the cylinder. The valve seats are circular rings of hardened metal which protect the relatively soft metal of the cylinder head from the hammering action of the valves and from the exhaust gases.

The cylinder heads of air-cooled engines are subjected to extreme temperatures; it is therefore necessary to provide adequate fin area, and to use metals which conduct heat rapidly. Cylinder heads of air-cooled engines are usually cast or forged singly. Aluminum alloy is used in the construction for a number of reasons. It is well adapted for casting or for the machining of deep, closely spaced fins, and it is more resistant than most metals to the corrosive attack of tetraethyl lead in gasoline. The greatest improvement in air cooling has resulted from reducing the thickness of the fins and increasing their depth. In this way the fin area has been increased from approximately 1,200 sq. in. to more than 7,500 sq. in. per cylinder in modern engines. Cooling fins taper from 0.090 in. at the base to 0.060 in. at the tip end. Because of the difference in temperature in the various sections of the cylinder head, it is necessary to provide more cooling-fin area on some sections than on others. The exhaust valve region is the hottest part of the internal surface; therefore, more fin area is provided around the outside of the cylinder in this section.

Cylinder Barrels

In general, the cylinder barrel in which the piston operates must be made of a high-strength material, usually steel. It must be as light as possible, yet have the proper characteristics for operating under high temperatures. It must be made of a good bearing material and have high tensile strength.

The cylinder barrel is made of a steel alloy forging with the inner surface hardened to resist wear of the piston and the piston rings which bear against it. This hardening is usually done by exposing the steel to ammonia or cyanide gas while the steel is very hot. The steel soaks up nitrogen from the gas which forms iron nitrides on the exposed surface. As a result of this process, the metal is said to be nitrided.

In some instances the barrel will have threads on the outside surface at one end so that it can be screwed into the cylinder head. Some air-cooled cylinder barrels have replaceable aluminum cooling fins attached to them, while others have the cooling fins machined as an integral part of the barrel.

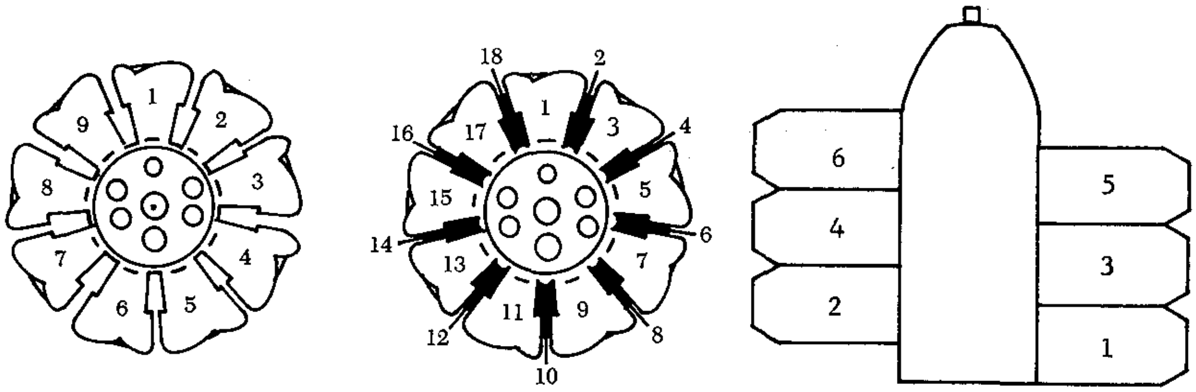
CYLINDER NUMBERING

Occasionally it is necessary to refer to the left or right side of the engine or to a particular cylinder. Therefore, it is necessary to know the engine directions and how cylinders of an engine are numbered.

The propeller shaft end of the engine is always the front end, and the accessory end is the rear end, regardless of how the engine is mounted in an aircraft. When referring to the right side or left side of an engine, always assume you are viewing it from the rear or accessory end. As seen from this position, crankshaft rotation is referred to as either clockwise or counterclockwise.

Radial engine cylinders are numbered clockwise as viewed from the accessory end. In-line and V-type engine cylinders are usually numbered from the rear. In V-engines, the cylinder banks are known as the right bank and the left bank, as viewed from the accessory end.

The numbering of engine cylinders is shown in figure 1–15. Note that the cylinder numbering of the opposed engine shown begins with the right rear as No. 1, and the left rear as No. 2. The one forward of No. 1 is No. 3; the one forward of No. 2, is No. 4, and so on. The numbering of opposed engine cylinders is by no means standard. Some manufacturers number their cylinders from the rear and others from the front of the engine. Always refer to the appropriate engine manual to determine the correct numbering system used by the manufacturer.



Single-row radial Double-row radial Opposed

FIGURE 1–15. Numbering of engine cylinders.

Single-row radial engine cylinders are numbered clockwise when viewed from the rear end. Cylinder No. 1 is the top cylinder. In double-row engines, the same system is used, in that the No. 1 cylinder is the top one in the rear row. No. 2 cylinder is the first one clockwise from No. 1, but No. 2 is in the front row. No. 3 cylinder is the next one clockwise to No. 2, but is in the rear row. Thus, all odd-numbered cylinders are in the rear row, and all even-numbered cylinders are in the front row.

FIRING ORDER

The firing order of an engine is the sequence in which the power event occurs in the different cylinders. The firing order is designed to provide for balance and to eliminate vibration to the greatest extent possible. In radial engines the firing order must follow a special pattern, since the firing impulses must follow the motion of the crankthrow during its rotation. In in-line engines the firing orders may vary somewhat, yet most orders are arranged so that the firing of cylinders is evenly distributed along the crankshaft. Six-cylinder in-line engines generally have a firing order of 1–5–3–6–2–4. Cylinder firing order in opposed engines can usually be listed in pairs of cylinders, as each pair fires across the center main bearing. The firing order of six-cylinder opposed engines is 1–4–5–2–3–6. The firing order of one model four-cylinder opposed engine is 1–4–2–3, but on another model it is 1–3–2–4.

Single-Row Radial Engines

On a single-row radial engine, first, all the odd-numbered cylinders fire in numerical succession; then the even-numbered cylinders fire in numerical succession. On a five-cylinder radial engine, for example, the firing order is 1–3–5–2–4, and on a seven-cylinder radial engine it is 1–3–5–7–2–4–6. The firing order of a nine-cylinder radial engine is 1–3–5–7–9–2–4–6–8.

Double-Row Radial Engines

On a double-row radial engine, the firing order is somewhat complicated. The firing order is arranged with the firing impulse occurring in a cylinder in one row and then in a cylinder in the other row; therefore, two cylinders in the same row never fire in succession.

An easy method for computing the firing order of a 14-cylinder, double-row radial engine is to start with any number from 1 to 14, and ***add 9 or subtract 5*** (these are called the firing order numbers), whichever will give an answer between 1 and 14, inclusive. For example, starting with 8, 9 cannot be added since the answer would then be more than 14; therefore, subtract 5 from 8 to get 3, add 9 to 3 to get 12, subtract 5 from 12 to get 7, subtract 5 from 7 to get 2, and so on.

The firing order numbers of an 18-cylinder, double-row radial engine are 11 and 7; that is, begin with any number from 1 to 18 and ***add 11 or subtract 7***. For example, beginning with 1, add 11 to get 12; 11 cannot be added to 12 because the total would be more than 18, so subtract 7 to get 5, add 11 to 5 to get 16, subtract 7 from 16 to get 9, subtract 7 from 9 to get 2, add 11 to 2 to get 13, and continue this process for 18 cylinders.

VALVES

The fuel/air mixture enters the cylinders through the intake valve ports, and burned gases are expelled through the exhaust valve ports. The head of each valve opens and closes these cylinder ports. The valves used in aircraft engines are the conventional poppet type. The valves are also typed by their shape and are called either mushroom or tulip because of their resemblance to the shape of these plants. Figure 1–16 illustrates various shapes and types of these valves.

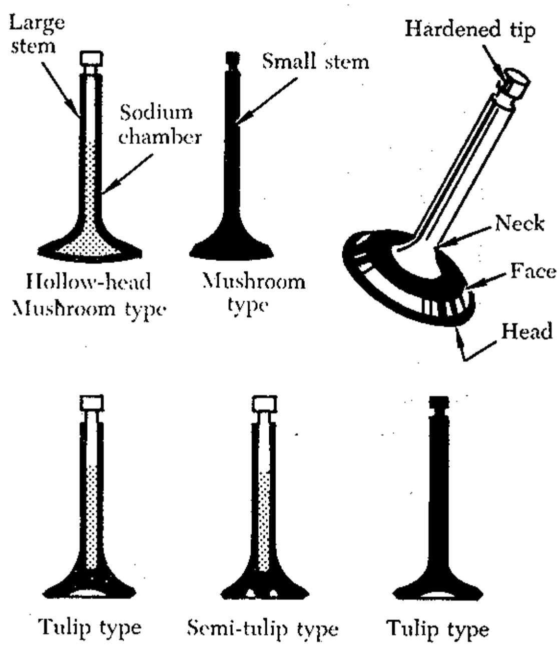


FIGURE 1–16. Valve types.

Valve Construction

The valves in the cylinders of an aircraft engine are subjected to high temperatures, corrosion, and operating stresses; thus, the metal alloy in the valves must be able to resist all these factors.

Because intake valves operate at lower temperatures than exhaust valves, they can be made of chrome-nickel steel. Exhaust valves are usually made of nichrome, silchrome, or cobalt-chromium steel.

The valve head has a ground face which forms a seal against the ground valve seat in the cylinder head when the valve is closed. The face of the valve is usually ground to an angle of either 30° or 45°. In some engines, the intake-valve face is ground to an angle of 30°, and the exhaust valve face is ground to a 45° angle.

Valve faces are often made more durable by the application of a material called stellite. About 1/16 inch of this alloy is welded to the valve face and ground to the correct angle. Stellite is resistant to high-temperature corrosion and also withstands the shock and wear associated with valve operation. Some engine manufacturers use a nichrome facing on the valves. This serves the same purpose as the stellite material.

The valve stem acts as a pilot for the valve head and rides in the valve guide installed in the cylinder head for this purpose. The valve stem is surface-hardened to resist wear. The neck is the part that forms the junction between the head and the stem. The tip of the valve is hardened to withstand the hammering of the valve rocker arm as it opens the valve. A machined groove on the stem near the tip receives the split-ring stem keys. These stem keys form a lock ring to hold the valve spring retaining washer in place.

Some intake and exhaust valve stems are hollow and partially filled with metallic sodium. This material is used because it is an excellent heat conductor. The sodium will melt at approximately 208° F., and the reciprocating motion of the valve circulates the liquid sodium and enables it to carry away heat from the valve head to the valve stem, where it is dissipated through the valve guide to the cylinder head and the cooling fins. Thus, the operating temperature of the valve may be reduced as much as 300° to 400° F. Under no circumstances should a sodium-filled valve be cut open or subjected to treatment which may cause it to rupture. Exposure of the sodium in these valves to the outside air will result in fire or explosion with possible personal injury.

The most commonly used intake valves have solid stems, and the head is either flat or tulip shaped. Intake valves for low-power engines are usually flat headed.

In some engines, the intake valve may be the tulip type and have a smaller stem than the exhaust valve, or it may be similar to the exhaust valve but have a solid stem and head. Although these valves are similar, they are not interchangeable since the faces of the valves are constructed of different material. The intake valve will usually have a flat milled on the tip to identify it.

VALVE-OPERATING MECHANISM

For a reciprocating engine to operate properly, each valve must open at the proper time, stay open for the required length of time, and close at the proper time. Intake valves are opened just before the piston reaches top dead center, and exhaust valves remain open after top dead center. At a particular instant, therefore, both valves are open at the same time (end of the exhaust stroke and beginning of the intake stroke). This valve-overlap permits better volumetric efficiency and lowers the cylinder operating temperature. This timing of the valves is controlled by the valve-operating mechanism.

The valve lift (distance that the valve is lifted off its seat) and the valve duration (length of time the valve is held open) are both determined by the shape of the cam lobes.

Typical cam lobes are illustrated in figure 1–17. The portion of the lobe that gently starts the valve-operating mechanism moving is called a ramp, or step. The ramp is machined on each side of the cam lobe to permit the rocker arm to be eased into contact with the valve tip and thus reduce the shock load which would otherwise occur.

The valve-operating mechanism consists of a cam ring or camshaft equipped with lobes, which work against a cam roller or a cam follower. (See figs. 1–18 and 1–19.) The cam follower, in turn, pushes a push rod and ball socket, which, in turn, actuates a rocker arm which opens the valve. Springs, which slip over the stem of the valves and which are held in place by the valve-spring retaining washer and stem key, close each valve and push the valve mechanism in the opposite direction when the cam roller or follower rolls along a low section of the cam ring.

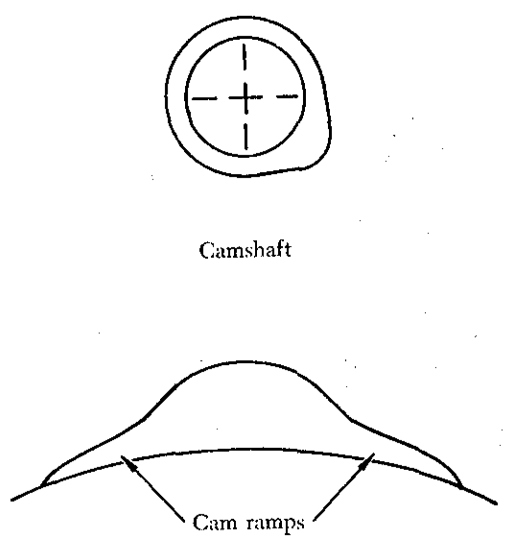


FIGURE 1–17. Typical cam lobes.

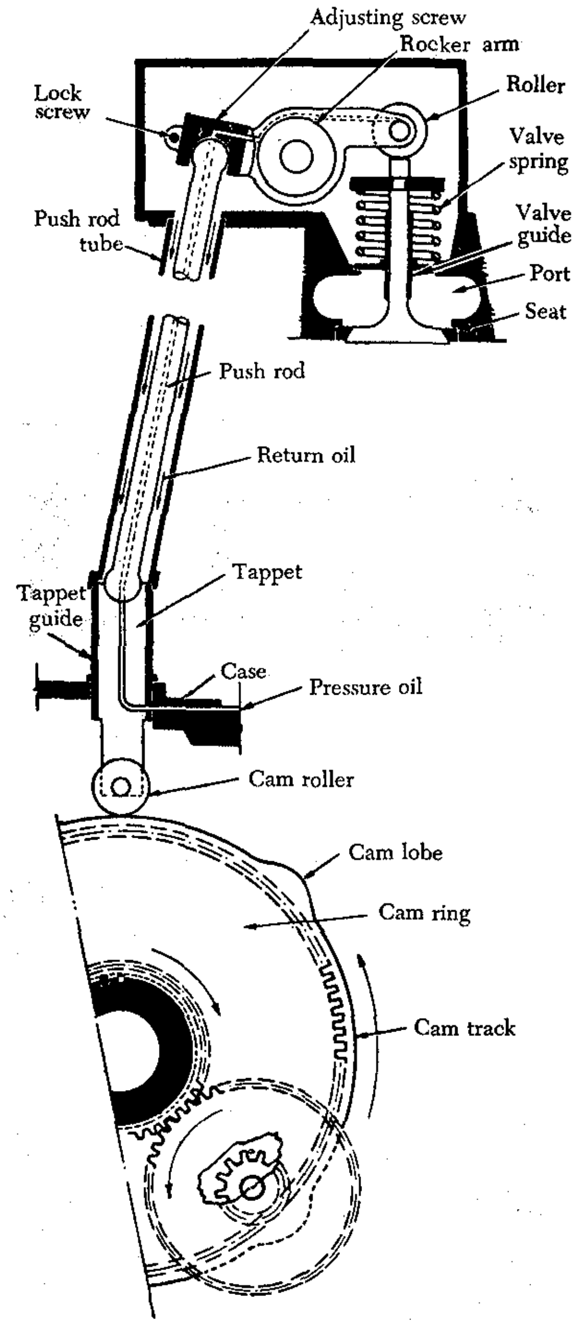


FIGURE 1–18. Valve-operating mechanism (radial engine).

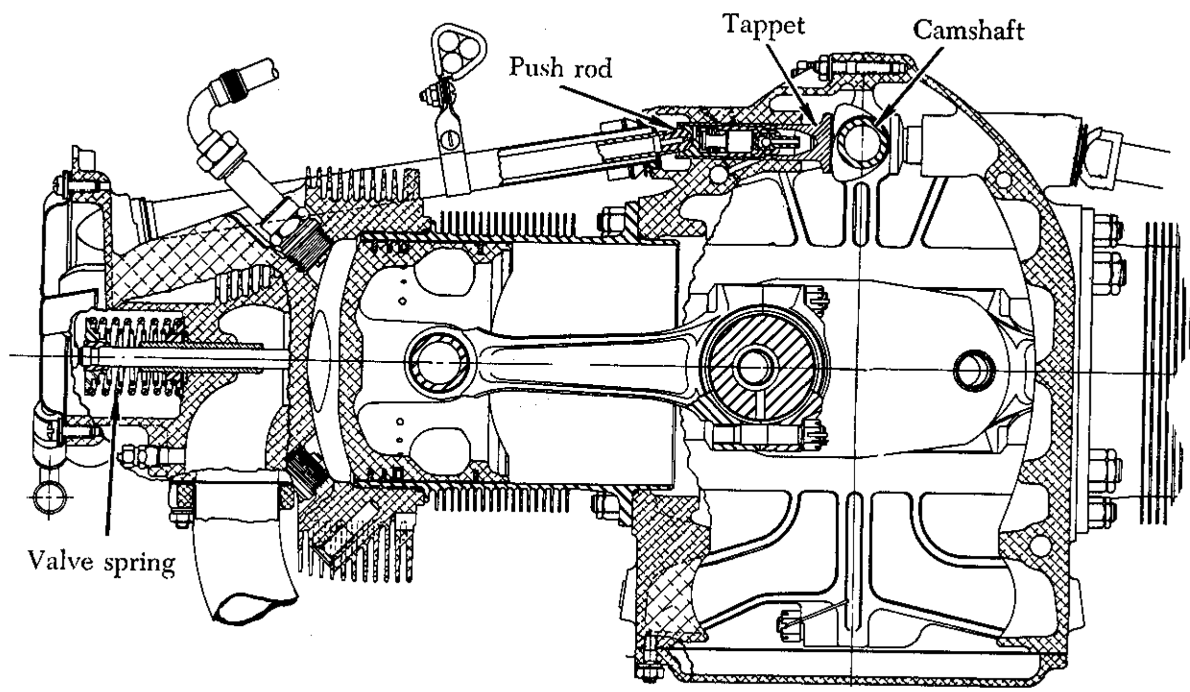


FIGURE 1–19. Valve-operating mechanism (opposed engine).

Cam Ring

The valve mechanism of a radial engine is operated by one or two cam rings, depending upon the number of rows of cylinders. In a single-row radial engine one ring with a double cam track is used. One track operates the intake valves; the other, the exhaust valves. The cam ring is a circular piece of steel with a series of cams or lobes on the outer surface. The surface of these lobes and the space between them (on which the cam rollers ride) is known as the cam track. As the cam ring revolves, the lobes cause the cam roller to raise the tappet in the tappet guide, thereby transmitting the force through the push rod and rocker arm to open the valve.

In a single-row radial engine, the cam ring is usually located between the propeller reduction gearing and the front end of the power section. In a twin-row radial engine, a second cam for the operation of the valves in the rear row is installed between the rear end of the power section and the supercharger section.

The cam ring is mounted concentrically with the crankshaft and is driven by the crankshaft at a reduced rate of speed through the cam intermediate drive gear assembly. The cam ring has two parallel sets of lobes spaced around the outer periphery, one set (cam track) for the intake valves and the other for the exhaust valves. The cam rings used may have four or five lobes on both the intake and the exhaust tracks. The timing of the valve events is determined by the spacing of these lobes and the speed and direction at which the cam rings are driven in relation to the speed and direction of the crankshaft.

The method of driving the cam varies on different makes of engines. The cam ring can be designed with teeth on either the inside or outside periphery. If the reduction gear meshes with the teeth on the outside of the ring, the cam will turn in the direction of rotation of the crankshaft. If the ring is driven from the inside, the cam will turn in the opposite direction from the crankshaft. This method is illustrated in figure 1–18.

A study of figure 1–20 will show that a four-lobe cam may be used on either a seven-cylinder or nine-cylinder engine. On the seven-cylinder it will rotate in the same direction as the crankshaft, and on the nine-cylinder, opposite the crankshaft rotation. On the nine-cylinder engine the spacing between cylinders is 40°, and the firing order is 1–3–5–7–9–2–4–6–8. This means that there is a space of 80° between firing impulses. The spacing on the four lobes of the cam ring is 90°, which is greater than the spacing between impulses. Therefore, to obtain proper relation of valve operations and firing order, it is necessary to drive the cam opposite the crankshaft rotation.

5 cylinders		7 cylinders		9 cylinders		
Number of lobes	Speed	Number of lobes	Speed	Number of lobes	Speed	Direction of rotation
3	1/6	4	1/8	5	1/10	With crankshaft.
2	1/4	3	1/6	4	1/8	Opposite crankshaft.

FIGURE 1–20. Radial engines, cam ring table.

Using the four-lobe cam on the seven-cylinder engine, the spacing between the firing of the cylinders will be greater than the spacing of the cam lobes. Therefore, it will be necessary for the cam to rotate in the same direction as the crankshaft.

A formula that sometimes is used in figuring cam speed is: Cam ring speed $= 1/2 \div$ by the number of lobes on either cam track.

One-half is the speed at which the cam would operate if it were equipped with a single lobe for each valve. It is divided by the number of lobes, which will determine how much the speed will have to be reduced.

In a twin-row, 14-cylinder radial engine which has seven cylinders in each row or bank, the valve mechanism may consist of two separate assemblies, one for each row. It could be considered as two seven-cylinder engines in tandem having the firing impulses properly spaced or lapped. For instance, in a twin-row engine, two four-lobe cam rings may be used. The cams are driven by gears attached to the crankshaft through gear teeth on the periphery of each cam.

Camshaft

The valve mechanism of an opposed engine is operated by a camshaft. The camshaft is driven by a gear that mates with another gear attached to the crankshaft (see figure 1–21). The camshaft always rotates at one-half the crankshaft speed. As the camshaft revolves, the lobes cause the tappet assembly to rise in the tappet guide, transmitting the force through the push rod and rocker arm to open the valve.

Tappet Assembly

The tappet assembly consists of:

(1) A cylindrical tappet, which slides in and out in a tappet guide installed in one of the crankcase sections around the cam ring.

(2) A cam follower or tappet roller, which follows the contour of the cam ring and lobes.

(3) A tappet ball socket or push rod socket.

(4) A tappet spring.

The function of the tappet assembly is to convert the rotational movement of the cam lobe into reciprocating motion and to transmit this motion to the push rod, rocker arm, and then to the valve tip, opening the valve at the proper time. The purpose of the tappet spring is to take up the clearance between the rocker arm and the valve tip to reduce the shock load when the valve is opened. A hole is drilled through the tappet to allow engine oil to flow to the hollow push rods to lubricate the rocker assemblies.

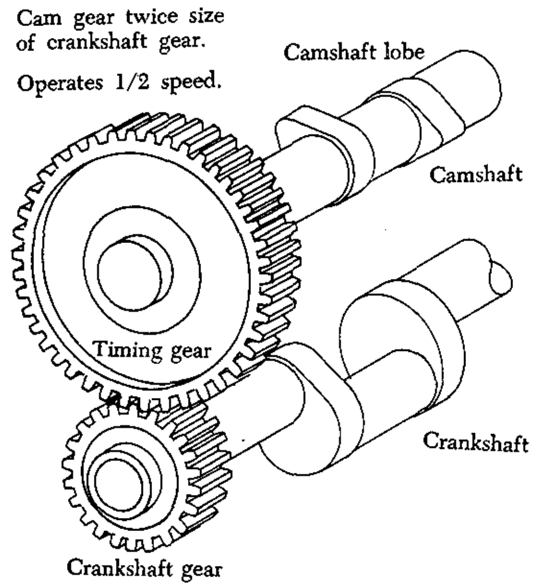


FIGURE 1–21. Cam drive mechanism opposed-type aircraft engine.

Hydraulic Valve Tappets

Some aircraft engines incorporate hydraulic tappets which automatically keep the valve clearance at zero, eliminating the necessity for any valve clearance adjustment mechanism. A typical hydraulic tappet (zero-lash valve lifter) is shown in figure 1–22.

When the engine valve is closed, the face of the tappet body (cam follower) is on the base circle or back of the cam, as shown in figure 1–22. The light plunger spring lifts the hydraulic plunger so that its outer end contacts the push rod socket, exerting a light pressure against it, thus eliminating any clearance in the valve linkage. As the plunger moves outward, the ball check valve moves off its seat. Oil from the supply chamber, which is directly connected with the engine lubrication system, flows in and fills the pressure chamber. As the camshaft rotates, the cam pushes the tappet body and the hydraulic lifter cylinder outward. This

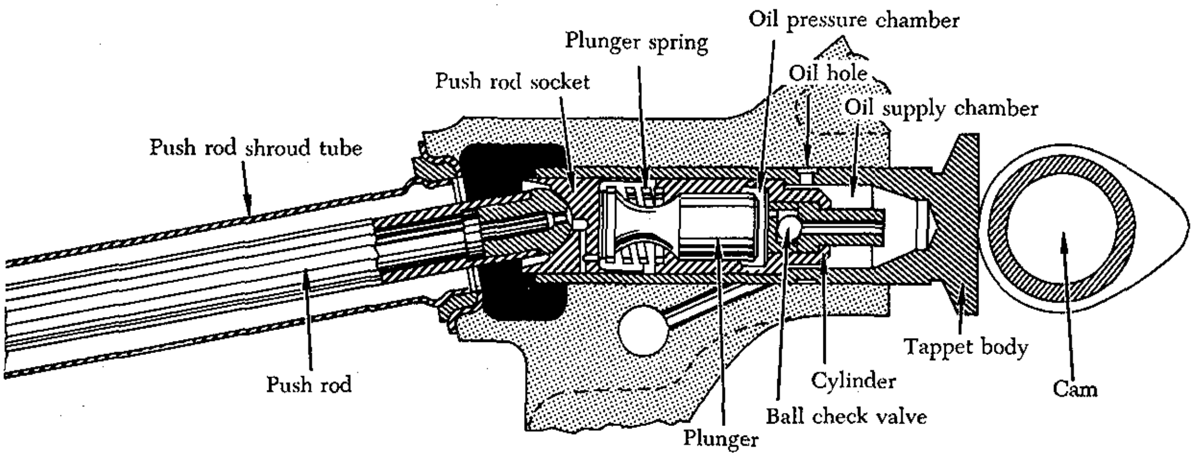


FIGURE 1–22. Hydraulic valve tappets.

action forces the ball check valve onto its seat; thus, the body of oil trapped in the pressure chamber acts as a cushion. During the interval when the engine valve is off its seat, a predetermined leakage occurs between plunger and cylinder bore which compensates for any expansion or contraction in the valve train. Immediately after the engine valve closes, the amount of oil required to fill the pressure chamber flows in from the supply chamber, preparing for another cycle of operation.

Push Rod

The push rod, tubular in form, transmits the lifting force from the valve tappet to the rocker arm. A hardened-steel ball is pressed over or into each end of the tube. One ball end fits into the socket of the rocker arm. In some instances the balls are on the tappet and rocker arm, and the sockets are on the push rod. The tubular form is employed because of its lightness and strength. It permits the engine lubricating oil under pressure to pass through the hollow rod and the drilled ball ends to lubricate the ball ends, rocker-arm bearing, and valve-stem guide. The push rod is enclosed in a tubular housing that extends from the crankcase to the cylinder head.

Rocker Arms

The rocker arms transmit the lifting force from the cams to the valves. Rocker arm assemblies are supported by a plain, roller, or ball bearing, or a combination of these, which serves as a pivot. Generally one end of the arm bears against the push rod and the other bears on the valve stem. One end of the rocker arm is sometimes slotted to accommodate a steel roller. The opposite end is constructed with either a threaded split clamp and locking bolt or a tapped hole.

The arm may have an adjusting screw for adjusting the clearance between the rocker arm and the valve stem tip. The screw is adjusted to the specified clearance to make certain that the valve closes fully.

Valve Springs

Each valve is closed by two or three helical-coiled springs. If a single spring were used, it would vibrate or surge at certain speeds. To eliminate this difficulty, two or more springs (one inside the other) are installed on each valve. Each spring will therefore vibrate at a different engine speed, and rapid damping out of all spring-surge vibrations during engine operation will result. Two or more springs also reduce danger of weakness and possible failure by breakage due to heat and metal fatigue.

The springs are held in place by split locks installed in the recess of the valve spring upper retainer or washer, and engage a groove machined into the valve stem. The functions of the valve springs are to close the valve and to hold the valve securely on the valve seat.

Hydraulic Valve Lifters

Hydraulic valve lifters are normally adjusted at the time of overhaul. They are assembled dry (no lubrication), clearances checked, and adjustments are usually made by use of pushrods having different lengths. A minimum and maximum valve clearance is established. Any measurement between these extremes is acceptable but approximately half way between the extremes is desired. Hydraulic valve lifters require less maintenance, are better lubricated, and operate more quietly than the screw adjustment type.

BEARINGS

A bearing is any surface which supports, or is supported by, another surface. A good bearing must be composed of material that is strong enough to withstand the pressure imposed on it and should permit the other surface to move with a minimum of friction and wear. The parts must be held in position within very close tolerances to provide efficient and quiet operation, and yet allow freedom of motion. To accomplish this, and at the same time reduce friction of moving parts so that power loss is not excessive, lubricated bearings of many types are used. Bearings are required to take radial loads, thrust loads, or a combination of the two.

There are two ways in which bearing surfaces move in relation to each other. One is by the sliding movement of one metal against the other, and the second is for one surface to roll over the other. The three different types of bearings in general use are plain, roller, and ball (see figure 1–23).

Plain Bearings

Plain bearings are generally used for the crankshaft, cam ring, camshaft, connecting rods, and the accessory drive shaft bearings. Such bearings are usually subjected to radial loads only, although some have been designed to take thrust loads.

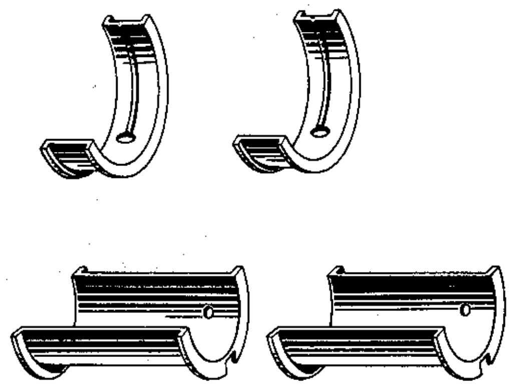
Plain bearings are usually made of nonferrous (having no iron) metals, such as silver, bronze, aluminum, and various alloys of copper, tin, or lead. Master rod or crankpin bearings in some engines are thin shells of steel, plated with silver on both the inside and the outside surfaces and with lead-tin plated over the silver on the inside surface only. Smaller bearings, such as those used to support various shafts in the accessory section, are called bushings. Porous Oilite bushings are widely used in this instance. They are impregnated with oil so that the heat of friction brings the oil to the bearing surface during engine operation.

Ball Bearings

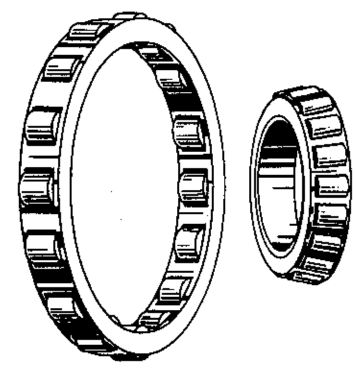
A ball bearing assembly consists of grooved inner and outer races, one or more sets of balls, and, in bearings designed for disassembly, a bearing retainer. They are used for supercharger impeller shaft bearings and rocker arm bearings in some engines. Special deep-groove ball bearings are used in aircraft engines to transmit propeller thrust to the engine nose section.

Roller Bearings

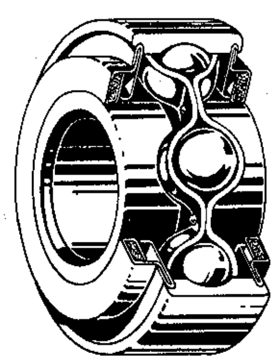
Roller bearings are made in many types and shapes, but the two types generally used in the aircraft engine are the straight roller and the tapered roller bearings. Straight roller bearings are used where the bearing is subjected to radial loads only. In tapered roller bearings, the inner- and outer-race bearing surfaces are cone shaped. Such bearings will withstand both radial and thrust loads. Straight roller bearings are used in high-power aircraft engines for the crankshaft main bearings. They are also used in other applications where radial loads are high.



Plain



Roller



Ball

FIGURE 1–23. Bearings.

PROPELLER REDUCTION GEARING

The increased brake horsepower delivered by a high-horsepower engine results partly from increased crankshaft r.p.m. It is therefore necessary to provide reduction gears to limit the propeller rotation speed to a value at which efficient operation is obtained. Whenever the speed of the blade tips approaches the speed of sound, the efficiency of the propeller decreases rapidly. The general practice has been to provide reduction gearing for propellers of engines whose speeds are above 2,000 r.p.m., because propeller efficiency decreases rapidly above this speed.

Since reduction gearing must withstand extremely high stresses, the gears are machined from steel forgings. Many types of reduction gearing systems are in use. The three types (fig. 1–24) most commonly used are:

(1) Spur planetary.
(2) Bevel planetary.
(3) Spur and pinion.

The planetary reduction gear systems are used with radial and opposed engines, and the spur and pinion system is used with in-line and V-type engines. Two of these types, the spur planetary and the bevel planetary, are discussed here.

The spur planetary reduction gearing consists of a large driving gear or sun gear splined (and sometimes shrunk) to the crankshaft, a large stationary gear, called a bell gear, and a set of small spur planetary pinion gears mounted on a carrier ring. The ring is fastened to the propeller shaft, and the planetary gears mesh with both the sun gear and the stationary bell or ring gear. The stationary gear is bolted or splined to the front-section housing. When the engine is operating, the sun gear rotates. Because the planetary gears are meshed with this ring, they also must rotate. Since they also mesh with the stationary gear, they will walk or roll around it as they rotate, and the ring in which they are mounted will rotate the propeller shaft in the same direction as the crankshaft but at a reduced speed.

In some engines, the bell gear is mounted on the propeller shaft, and the planetary pinion gear cage is held stationary. The sun gear is splined to the crankshaft and thus acts as a driving gear. In such an arrangement, the propeller travels at a reduced speed, but in opposite direction to the crankshaft.

In the bevel planetary reduction gearing system, the driving gear is machined with beveled external teeth and is attached to the crankshaft. A set of mating bevel pinion gears is mounted in a cage attached to the end of the propeller shaft. The pinion gears are driven by the drive gear and walk around the stationary gear, which is bolted or splined to the front-section housing. The thrust of the bevel pinion gears is absorbed by a thrust ball bearing of special design. The drive and the fixed gears are generally supported by heavy-duty ball bearings. This type of planetary reduction assembly is more compact than the other one described and can therefore be used where a smaller propeller gear step-down is desired.

PROPELLER SHAFTS

Propeller shafts may be three major types; tapered, splined, or flanged. Tapered shafts are identified by taper numbers. Splined and flanged shafts are identified by SAE numbers.

The propeller shaft of most low-power output engines is forged as part of the crankshaft. It is tapered and a milled slot is provided so that the propeller hub can be keyed to the shaft. The keyway and key index of the propeller are in relation to the #1 cylinder top dead center. The end of the shaft is threaded to receive the propeller retaining nut. Tapered propeller shafts are common on older and in-line engines.

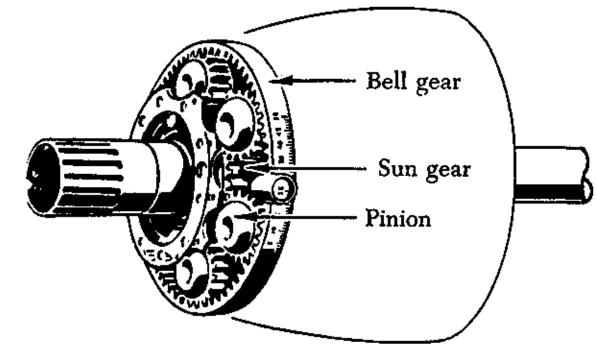
The propeller shaft of a high-output engine generally is splined. It is threaded on one end for a propeller hub nut. The thrust bearing, which absorbs propeller thrust, is located around the shaft and transmits the thrust to the nose-section housing. The shaft is threaded for attaching the thrust-bearing retaining nut. On the portion protruding from the housing (between the two sets of threads), splines are located to receive the splined propeller hub. The shaft is generally machined from a steel-alloy forging throughout its length. The propeller shaft may be connected by reduction gearing to the engine crankshaft, but in smaller engines the propeller shaft is simply an extension of the engine crankshaft. To turn the propeller shaft, the engine crankshaft must revolve.

Flanged propeller shafts are used on medium or low powered reciprocating and turbojet engines. One end of the shaft is flanged with drilled holes to accept the propeller mounting bolts. The installation may be a short shaft with internal threading to accept the distributor valve to be used with a controllable propeller. The flanged propeller shaft is a normal installation on most approved reciprocating engines.

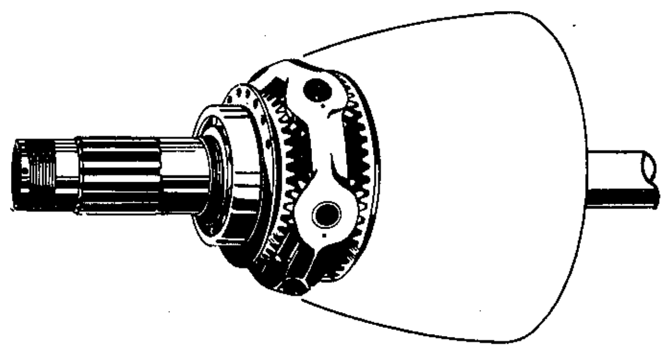
RECIPROCATING ENGINE OPERATING PRINCIPLES

A study of this section will help in understanding the basic operating principles of reciprocating engines. The principles which govern the relationship between the pressure, volume, and temperature of gases are the basic principles of engine operation.

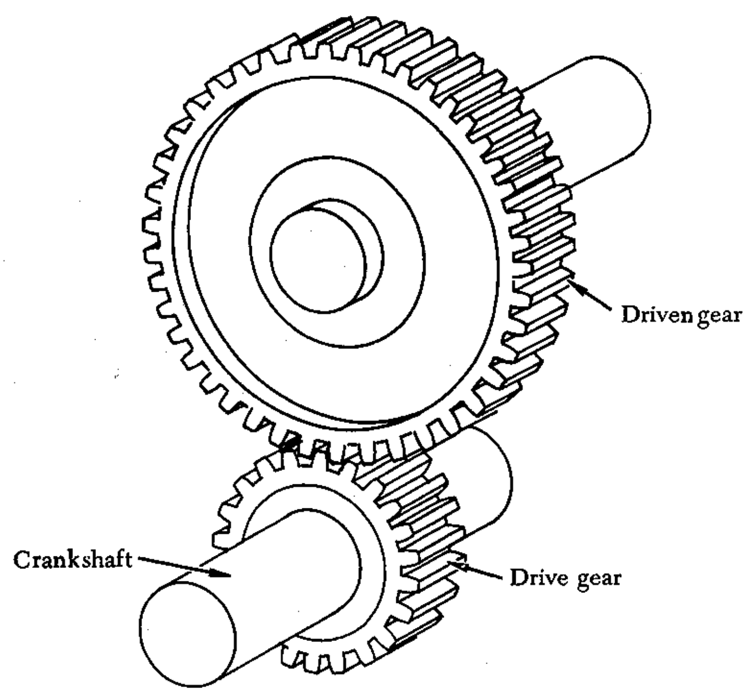
An internal-combustion engine is a device for converting heat energy into mechanical energy. Gasoline is vaporized and mixed with air, forced or drawn into a cylinder, compressed by a piston, and then ignited by an electric spark. The conversion of the resultant heat energy into mechancial energy and then into work is accomplished in the cylinder. Figure 1–25 illustrates the various engine compo-



Spur-planetary



Bevel planetary



Spur and pinion

FIGURE 1–24. Reduction gears.

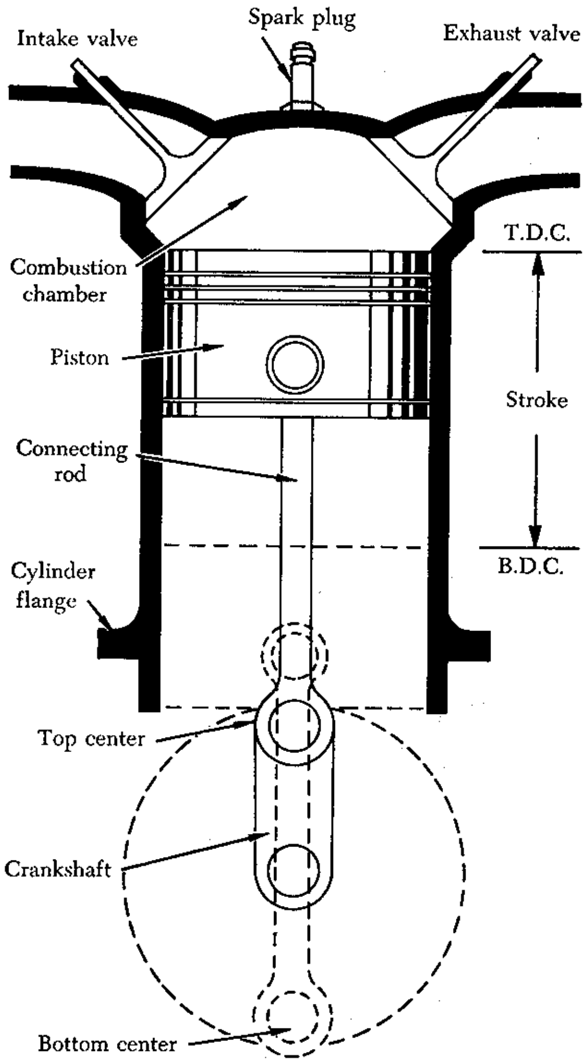


FIGURE 1–25. Components and terminology of engine operation.

nents necessary to accomplish this conversion and also presents the principal terms used to indicate engine operation.

The operating cycle of an internal combustion reciprocating engine includes the series of events required to induct, compress, ignite, burn, and expand the fuel/air charge in the cylinder, and to scavenge or exhaust the byproducts of the combustion process.

When the compressed mixture is ignited, the resultant gases of combustion expand very rapidly and force the piston to move away from the cylinder head. This downward motion of the piston, acting on the crankshaft through the connecting rod, is converted to a circular or rotary motion by the crankshaft.

A valve in the top or head of the cylinder opens to allow the burned gases to escape, and the momentum of the crankshaft and the propeller forces the piston back up in the cylinder where it is ready for the next event in the cycle. Another valve in the cylinder head then opens to let in a fresh charge of the fuel/air mixture.

The valve allowing for the escape of the burning exhaust gases is called the exhaust valve, and the valve which lets in the fresh charge of the fuel/air mixture is called the intake valve. These valves are opened and closed mechanically at the proper times by the valve-operating mechanism.

The bore of a cylinder is its inside diameter. The stroke is the distance the piston moves from one end of the cylinder to the other, specifically, from T.D.C. (top dead center) to B.D.C. (bottom dead center), or vice versa (see figure 1–25).

OPERATING CYCLES

There are two operating cycles in general use: (1) The two-stroke cycle, and (2) the four-stroke cycle. At the present time, the two-stroke-cycle engine is fast disappearing from the aviation scene and will not be discussed. As the name implies, two-stroke-cycle engines require only one upstroke and one downstroke of the piston to complete the required series of events in the cylinder. Thus the engine completes the operating cycle in one revolution of the crankshaft.

Most aircraft reciprocating engines operate on the four-stroke cycle, sometimes called the Otto cycle after its originator, a German physicist. The four-stroke-cycle engine has many advantages for use in aircraft. One advantage is that it lends itself readily to high performance through supercharging.

In this type of engine, four strokes are required to complete the required series of events or operating cycle of each cylinder, as shown in figure 1–26. Two complete revolutions of the crankshaft (720°) are required for the four strokes; thus, each cylinder in an engine of this type fires once in every two revolutions of the crankshaft.

FOUR-STROKE CYCLE

In the following discussion of the four-stroke-cycle engine operation, it should be realized that the timing of the ignition and the valve events will vary considerably in different engines. Many factors influence the timing of a specific engine, and it is most important that the engine manufacturer's recommendations in this respect be followed in maintenance and overhaul. The timing of the valve and ignition events is always specified in degrees of crankshaft travel.